# IACHEC Thermal SNRs Working Group Report

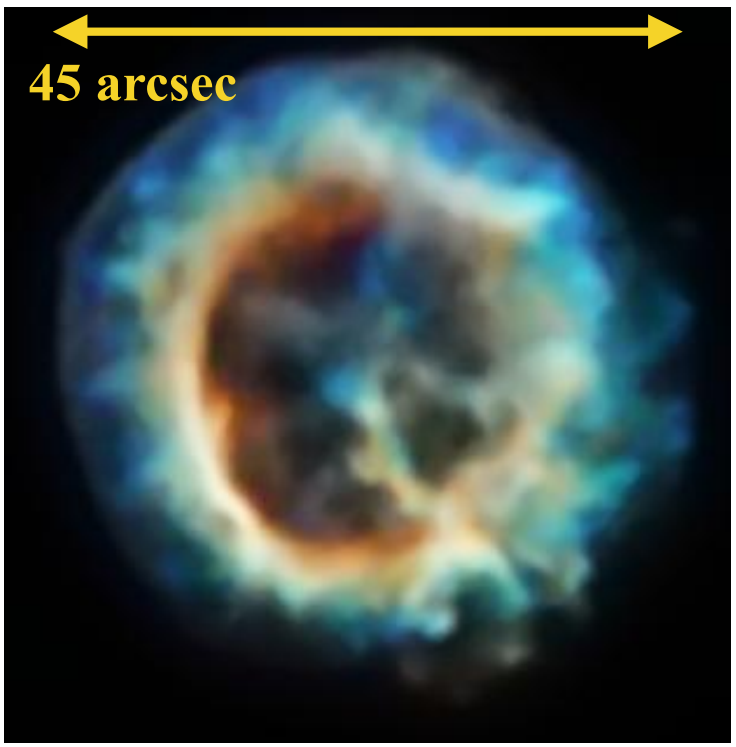
# Thermal SNRs WG Current Membership

**Andy Beardmore(Leicester), Sunil Chandra(CSRNWU), Konrad Dennerl(MPE), Jelle de Plaa(SRON), Gulab Dewangan(IUCAA), Adam Foster(SAO), Michael Freyberg(MPE), Terrance Gaetz(SAO), Brian Grefenstette(Caltech), Frank Haberl(MPE), Jelle Kaastra(SRON), Xi Long(SAO), Kristin Madsen(UMBC), Eric Miller(MIT), Paul Plucinsky(SAO), Andy Pollock(Sheffield), Manami Sasaki(Remeis Observatory & ECAP), Steve Sembay(Leicester), KP Singh(IISERM), Martin Stuhlinger(ESAC), Firoza Sutaria(TIFR), Hiroya Yamaguchi(ISAS)**

# E0102: IACHEC Efforts

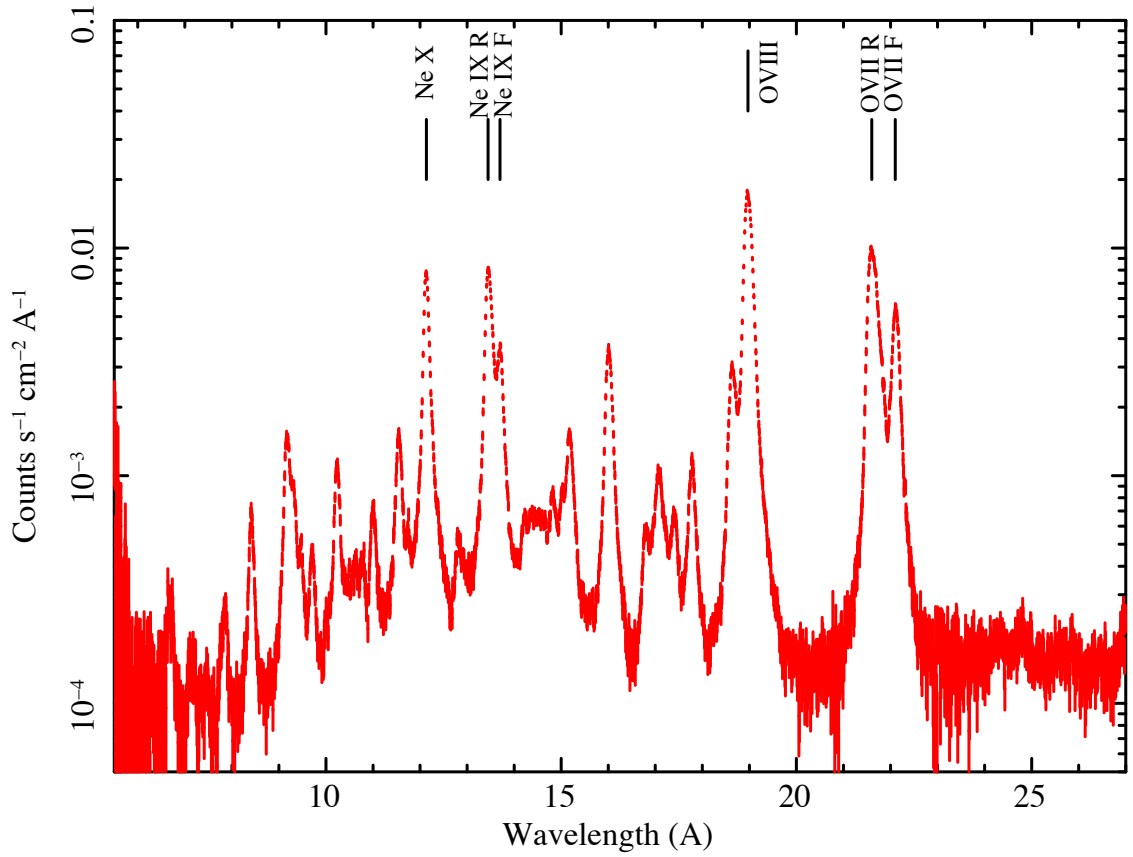
- XMM RGS spectrum shows strong, well-separated lines of O, Ne, & Mg (Rasmussen et al. 2001)
- IACHEC standard, empirical model published in Plucinsky et al. 2017, A&A, 597, A35
- Model is used by Chandra and was used by Suzaku to verify contamination models and by Swift, ASTROSAT and NICER to search for contamination, gain and other purposes
- key data set for the Concordance paper (ACIS, pn, MOS, Suzaku, Swift)
- model available at "https://wikis.mit.edu/confluence/display/iachec/Thermal+SNR"

**Chandra ACIS**




Red (0.3-0.5 keV), Green (0.5-0.75 keV)
Blue (0.75 – 7.0 keV)

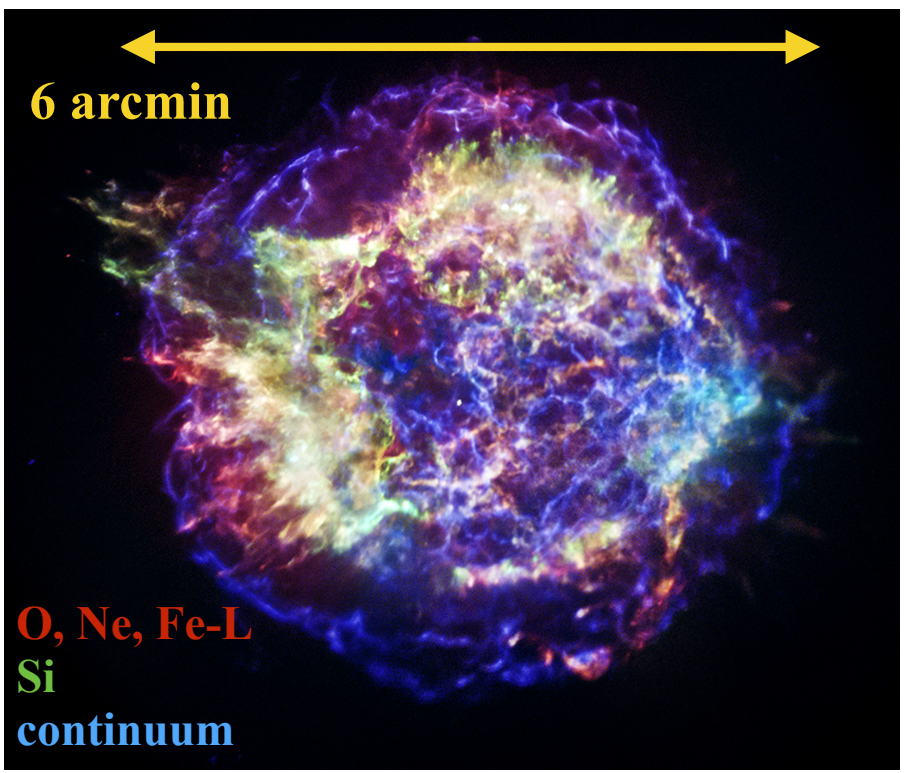
**XMM RGS** **Pollock (Sheffield)**



# Cas A: IACHEC Efforts

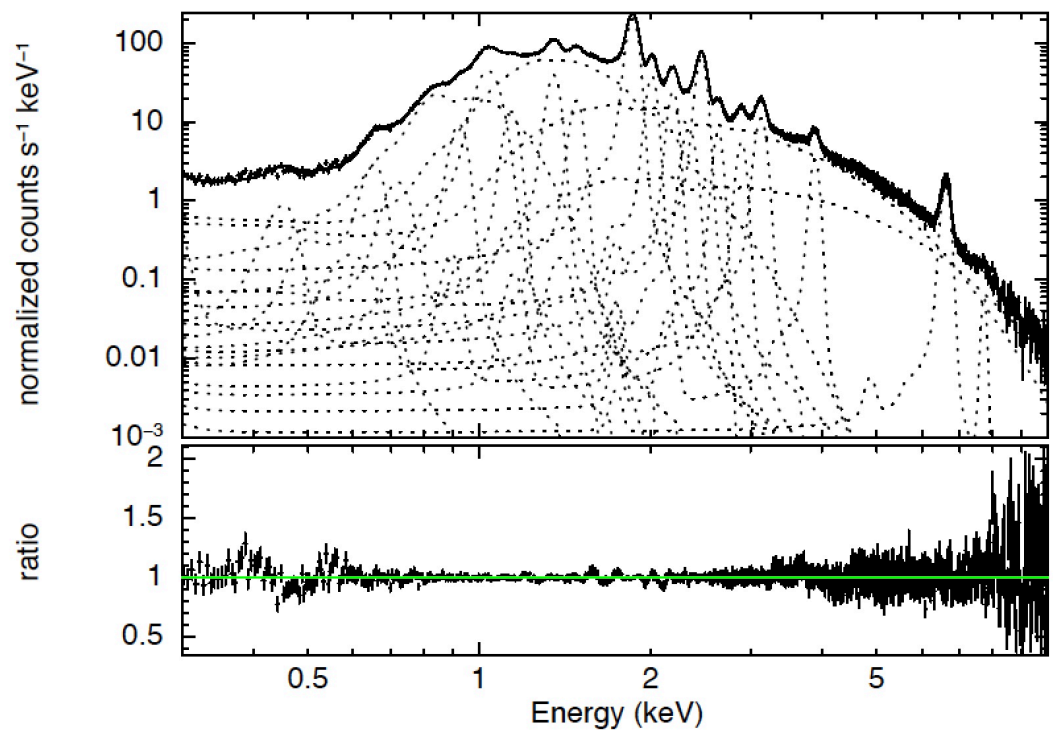
- Highest X-ray flux from a *thermal* SNR ($F_x$=2.6x10$^{-9}$ ergs cm$^{-2}$ s$^{-1}$ [0.3-10.0 keV])
- Beardmore (Leicester) developed an IACHEC standard, empirical model, available at "https://wikis.mit.edu/confluence/display/iachec/Cas+A"
- significant spectral variations with position due to different plasma conditions and bulk velocities
- CXC calibration team is starting to use Cas A in conjunction with the ACIS external calibration source for gain calibration
- Swift and ASTROSAT use Cas A for gain and CTI calibration

**Chandra ACIS**




**Beardmore (Leicester)**

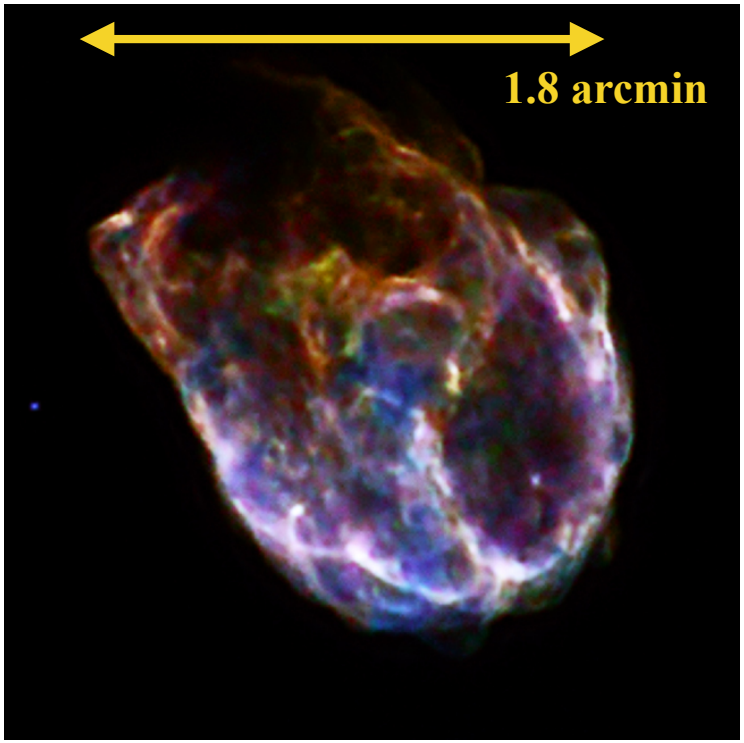
**XMM MOS1**



# N132D

- Most X-ray luminous SNR in the Local Group
- Spectrum is more complicated than E0102, significant Fe-L and Fe-K emission and multiple (identified) temperature components (Behar et al. 2000, Suzuki et al. 2020)
- More spectral variation with position & slightly larger than E0102
- Routine calibration target for XMM and Chandra LP in 2019/2020

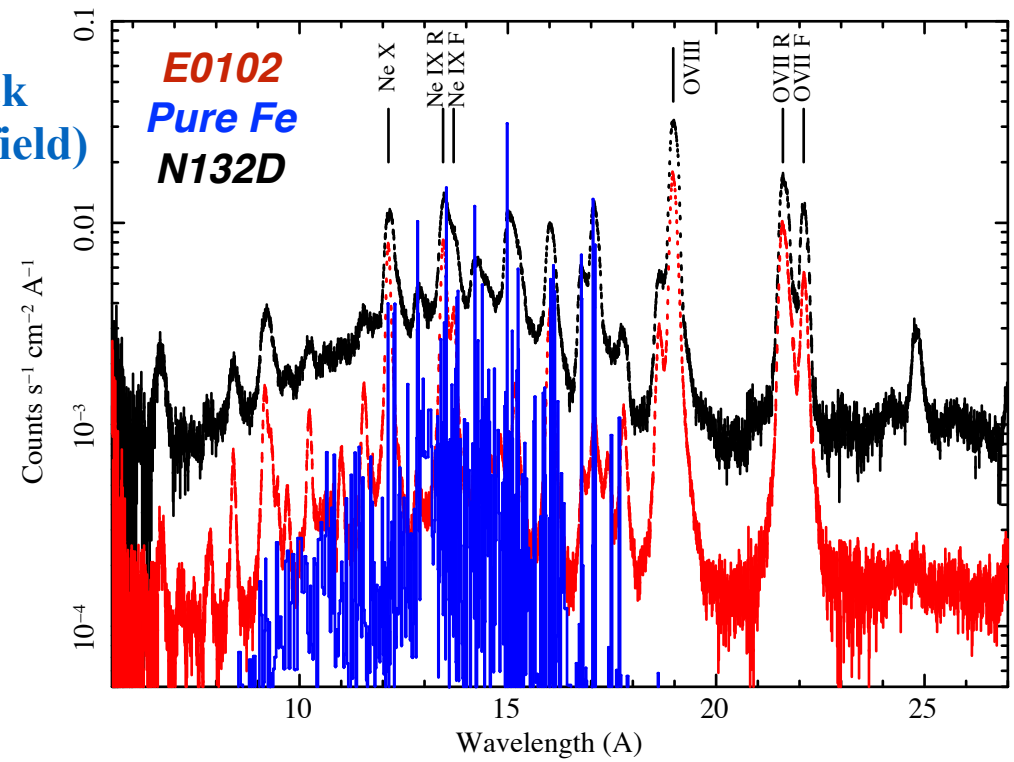
**Chandra ACIS**




Red (0.3-0.75 keV), Green (0.8-1.1 keV), Blue (1.1 – 2.0 keV)

**XMM RGS Spectra of N132D and E0102**

Pollock (Sheffield)



# N132D: Model Development

- WG is developing two models currently, an empirical model (abs., nlapec, Gaussians) and a physical model (abs., vrnei or vapec, Gaussian)
- RGS data has driven the empirical model in the 0.3-1.5 keV range. Stuhlinger, Pollock & Guainazzi developed first version in 2012.
- Suzuki et al. 2020 published an analysis of the 1st and 2nd order RGS spectra, used in the physical model.
- Empirical model currently consists of:

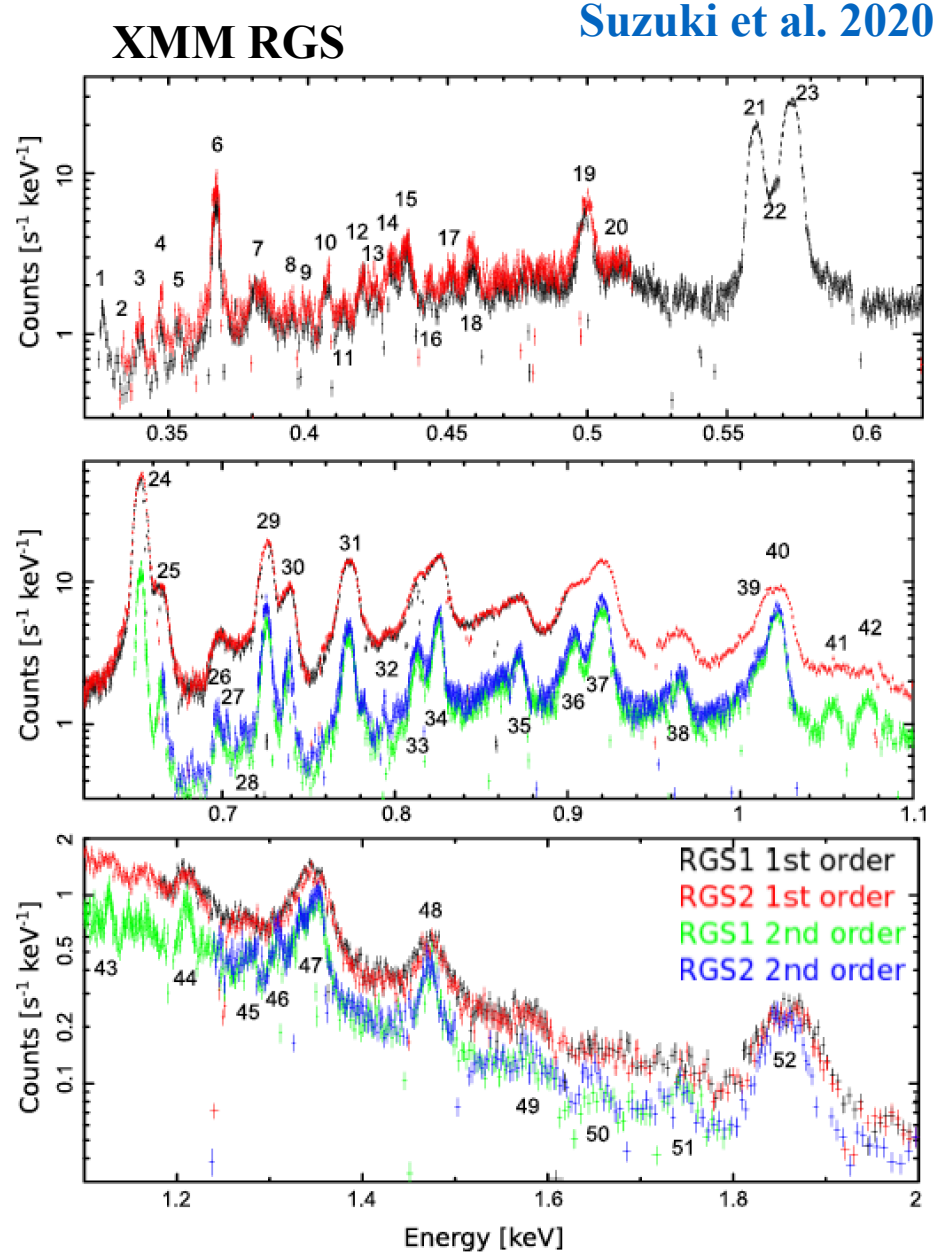
  - two components for absorption (Galactic and LMC)
  - 120 Gaussians for the lines
  - three nlapec components for the continuum with:

    $kT_1 = 0.18$ keV

    $kT_2 = 1.14$ keV

    $kT_3 = 5.48$ keV

Suzuki et al. 2020

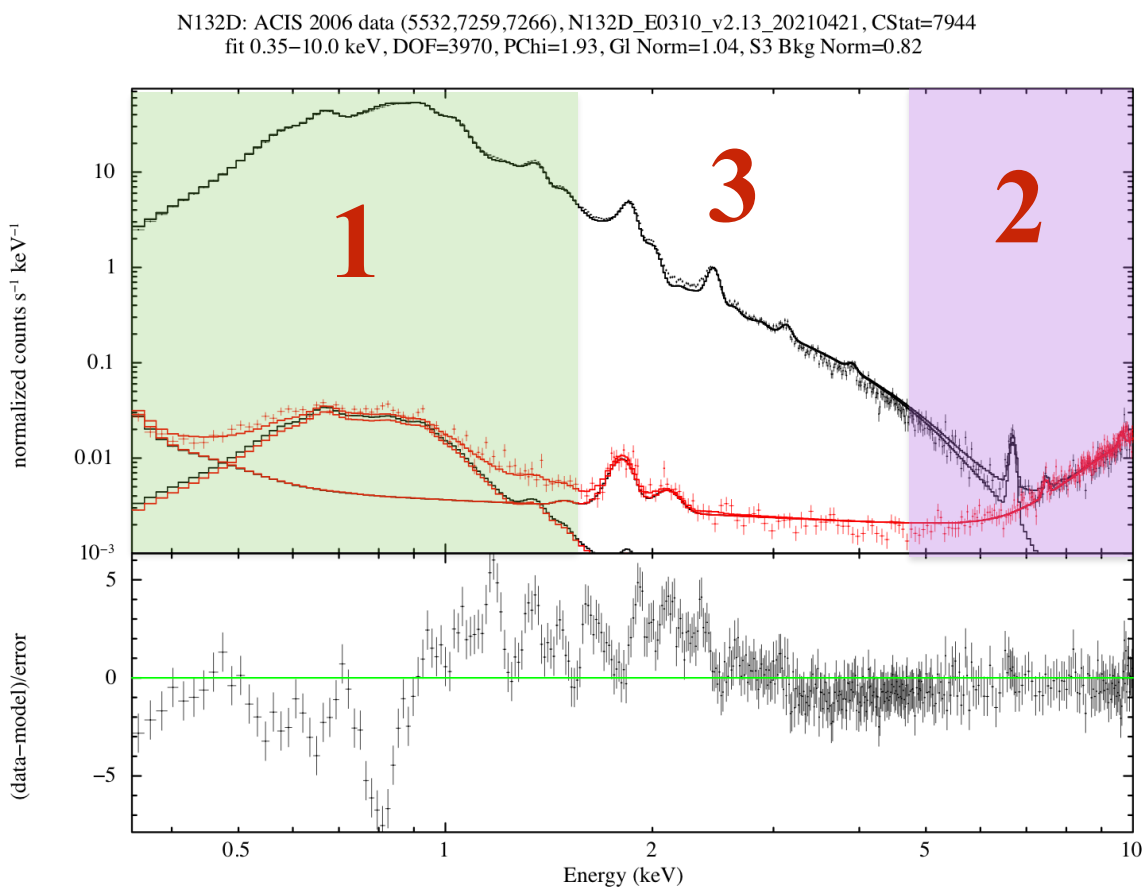


# N132D: Model Development

- We must develop the model in different stages (energy ranges), given the sensitivities of the various instruments
- Ideally we would go in order of flux, low energy range first, then the mid energy range next and finally the high energy range. But we jumped ahead to the high energy range
- We should correct this and go in order of flux

**0.3-1.5 keV: RGS**
**1.5-4.5 keV: pn, MOS, ACIS, XRT, XIS**
**4.5-8.0 keV: NuSTAR, pn, MOS, ACIS, XIS**

- Thermal SNRs WG has focussed recently on the high energy part of the spectrum taking advantage of the new information from NuSTAR (Grefenstette) and Suzaku (Miller), also Bamba et al. 2018
- Results presented at this meeting will focus on the 4.5-8.0 keV range



# N132D General Fitting Instructions

- **fit in the 4.5 - 8.0 keV band** (the 8.0 keV is flexible, do what makes sense for your instrument)
- **use unbinned spectra** for fitting or use Kaastra's optimal binning method using the ftool optimal binning (using 'ftgrouppha' with 'bintype=opt')
- **use an explicit background model** for your instrument, do not subtract background
- vary what parameters make sense for your background model, hopefully this is just a normalization
- **use the C statistic** as the fit statistic to determine the best fit
- use the Pearson chi square or chi square with the weighting by the model for test statistic
- report the C statistic, Pearson chi square and DOF for the fits
- run the goodness command in xspec with the default settings of "sim" and "fit" to evaluate the goodness of the fit.

# Physical Model Fitting Instructions

- **allow the global norm** to vary (**n132d:1**)
- Freeze the normalization of the high kT vrnei component (currently 4.77464 keV) and do NOT allow it to vary (**n132d:189**)
- set the neutral Fe K line normalization to 0 and freeze it (**n132d:192**)
- report C statistic, Pearson chi square, and DOF
- report the best fit value of the global normalization with 1 sigma uncertainty (this is the only free parameter in the source model)
- **report the flux in the 4.5–8.0 keV** band with 1 sigma uncertainty

**Model is called "n132d_afoster_suzuki_vrnei_20210420.mdl" and is available on the IACHEC wiki page:**
**https://wikis.mit.edu/confluence/display/iachec/Current+N132D+model**

***Only one free parameter in the source model, a global normalization. For this exercise, we are assuming a spectral shape, evaluating if that shape fits the data well. If yes, then we will compare the fitted values of the normalization and flux.***

# Empirical Model Fitting Instructions

- freeze the normalization of the neutral Fe line to 0.0
- **allow the Global Norm** to vary (**source:1**)
- freeze the normalization of the high kT component and do NOT allow it to vary (**source:419**)
- **allow the normalization of the Fe XXV He-alpha f line** (**source:390**) to vary, the normalizations of the Fe XXV He-alpha f and i lines are linked to the normalization of the Fe XXV He-alpha r line. So, only one normalization in the Fe XVV He-alpha triplet is allowed to vary.
- **allow the normalization of the Fe XXVI Ly-alpha line** (**source:399**) to vary
- there should be only three free parameters in the source model, source1, source:390, and source:399
- report C statistic, Pearson chi square, and DOF
- report the result of the goodness command
- report the best fitted values with 1 sigma uncertainties (delta C statistic of 1.0) for the Global Norm, normalization of the Fe XXV He-alpha r line, and the normalization of the Fe XXVI Ly-alpha line
- **report the flux in the 4.5-8.0 keV** band with 1 sigma uncertainty

***Only three free parameters in the source model, all are normalizations.***

**Model is called "N132D_E0310_v2.13_20210421.mdl" and is available on the IACHEC wiki page:**
**https://wikis.mit.edu/confluence/display/iachec/Current+N132D+model**

# The Spectral Fitters

## *Those who did the work:*

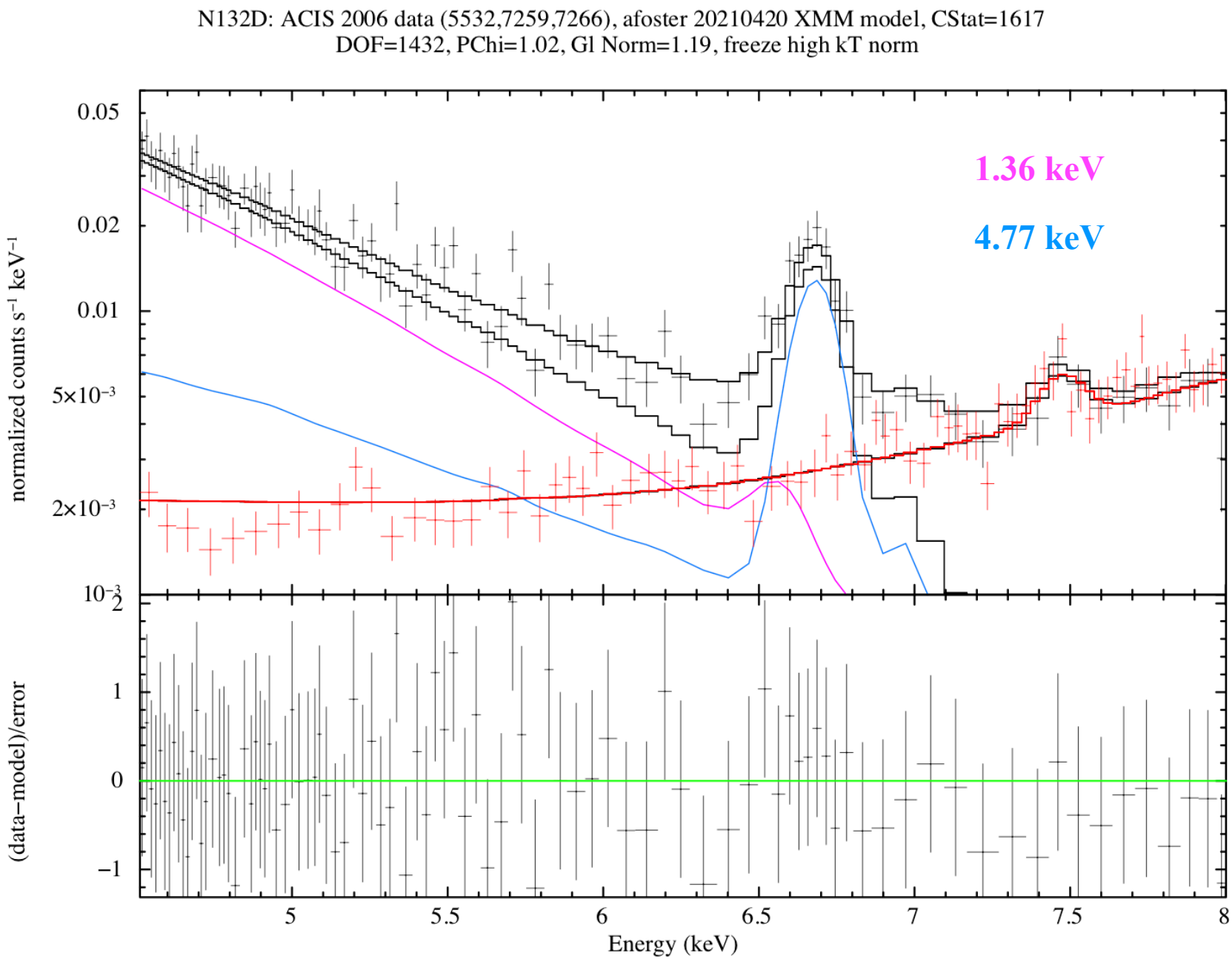
| | |
|---|---|
| NuSTAR | Brian Grefenstette (Caltech) |
| Suzaku XIS | Eric Miller (MIT) |
| XMM pn & MOS | Adam Foster (SAO) |
| Models | Adam Foster (SAO) |
| XMM-RGS | Martin Stuhlinger (ESAC) |
| Chandra ACIS | Paul Plucinsky (SAO) |
| Swift XRT | Andrew Beardmore (Leicester) |

# Development of Physical Model and Fits to the pn and MOS Data

Adam Foster presents this

**ACIS:**
**2006 data fit**
**4.5-8.0 keV with the physical model.**
**Only the global norm & detector norm are allowed to vary.**

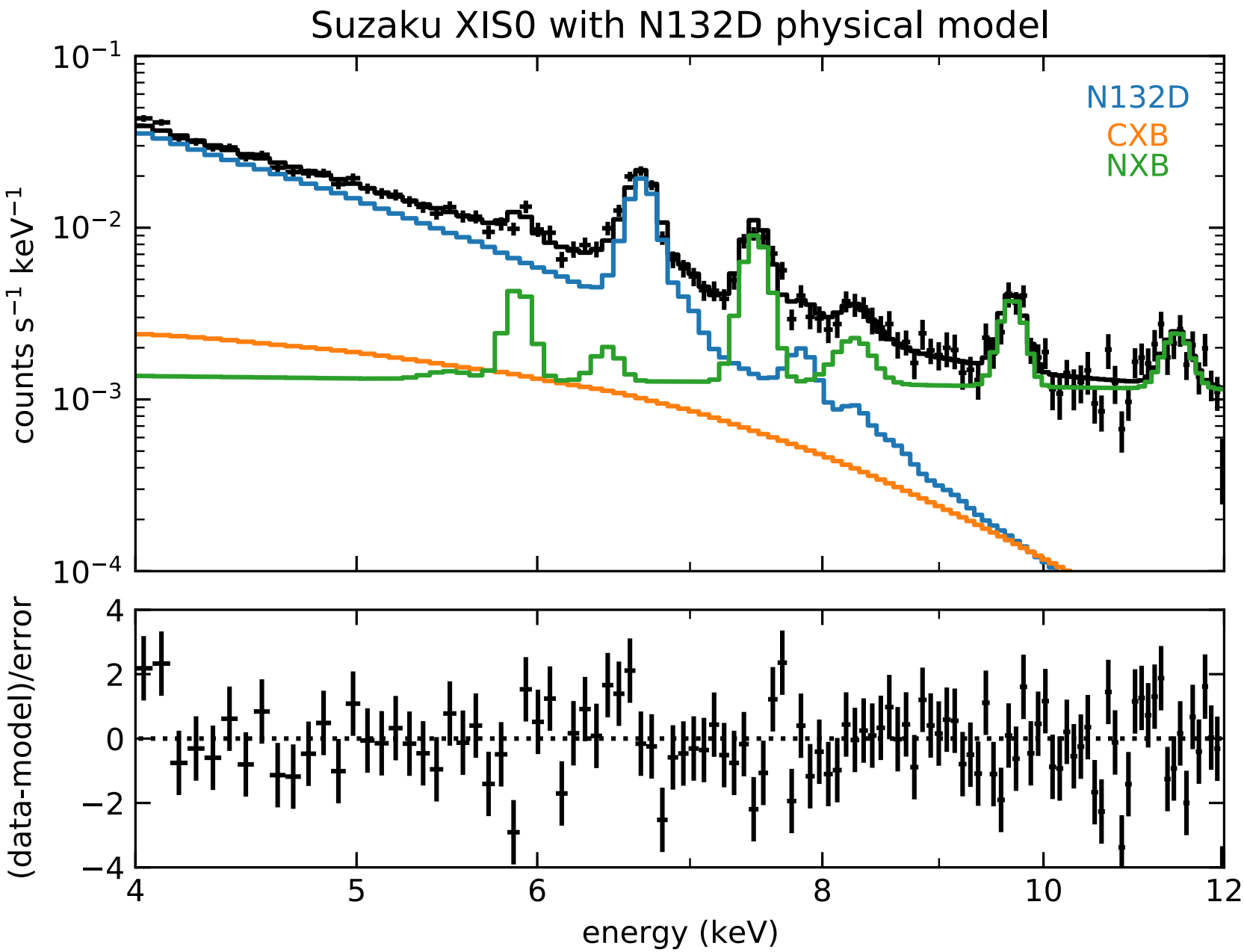
**Global Norm= 1.19**
**CStat=1617**
**DOF=1432**
**PChi=1.02**
**Goodness= 65.0%**



**Miller (MIT)**

**Suzaku XIS0: 4.5-8.0 keV with the physical model. Only the global norm & detector norm are allowed to vary.**

**Global Norm= 1.14**
**CStat=522**
**DOF=481**
**PChi=1.03**
**Goodness= 84.0%**

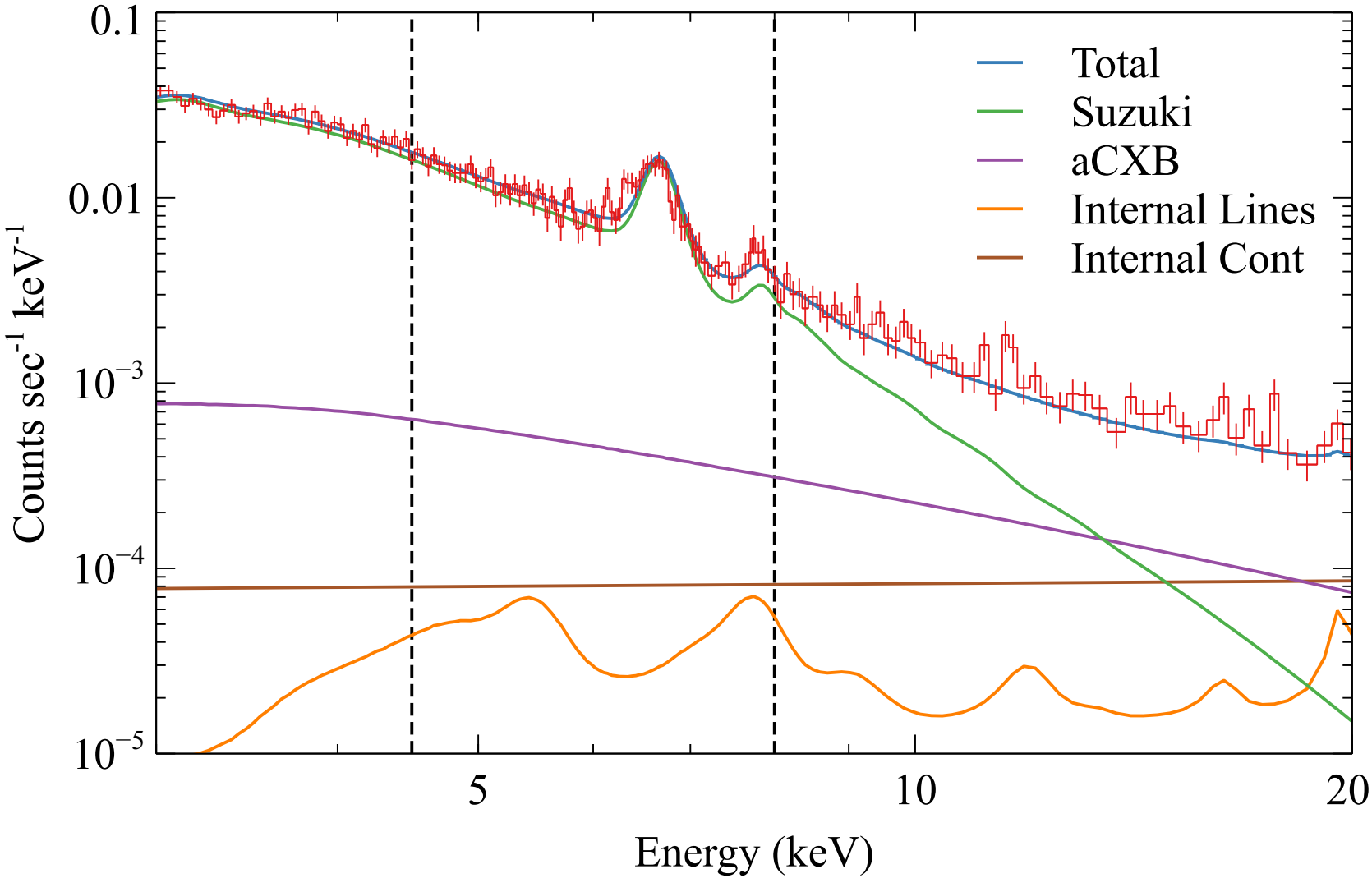


# Physical model, un-binned

Grefenstette (Caltech)

**NuSTAR : 4.5-8.0 keV FPMA& FPMB physical model. Only the global norm & detector norm are allowed to vary.**

**Global Norm= 1.04,1.15**
**CStat=179**
**DOF=169**
**PChi=1.09**
**Goodness= 76.0%**

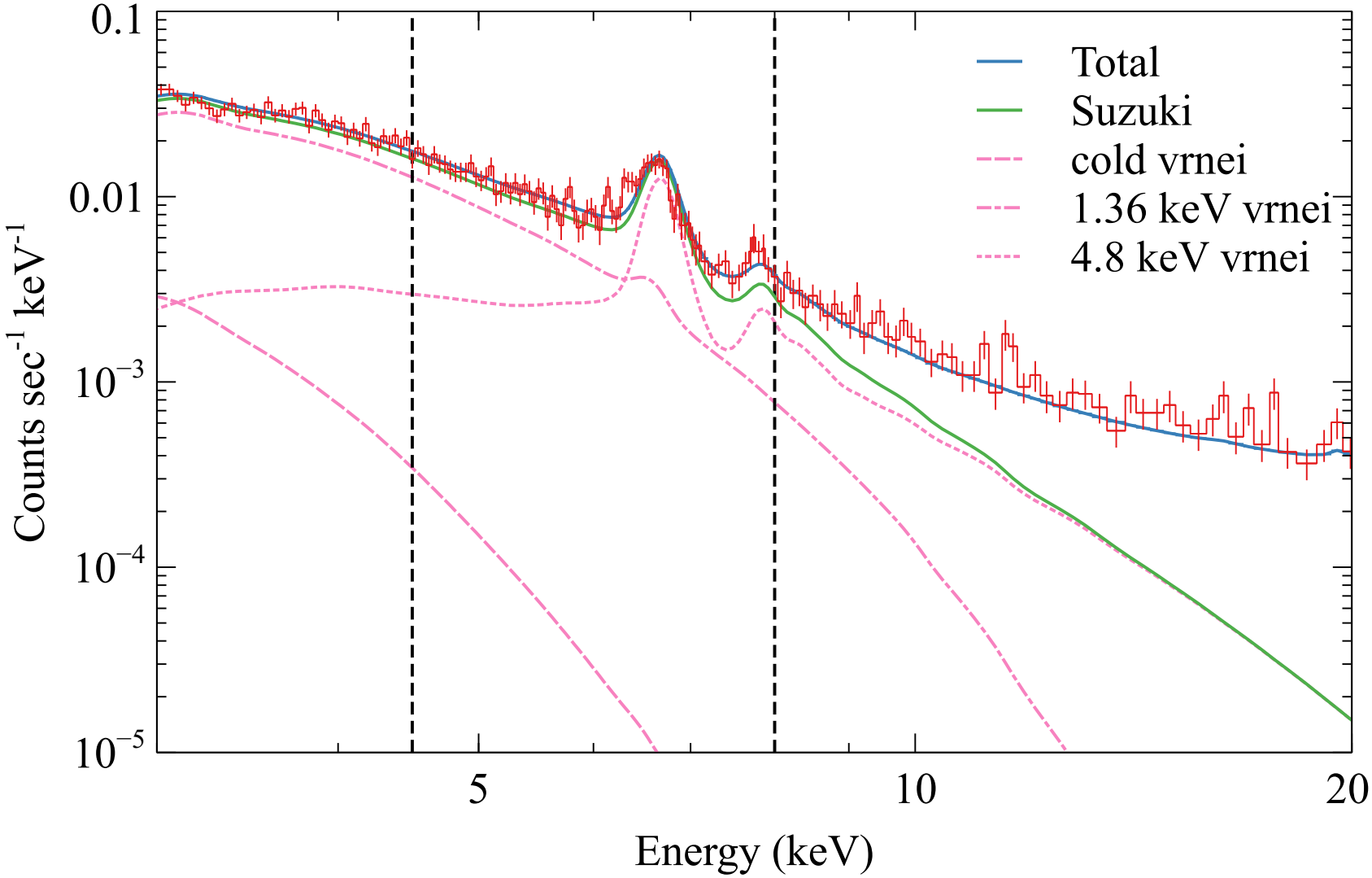


# Physical model, un-binned

**Grefenstette (Caltech)**

**NuSTAR : 4.5-8.0 keV FPMA& FPMB physical model. Only the global norm & detector norm are allowed to vary.**

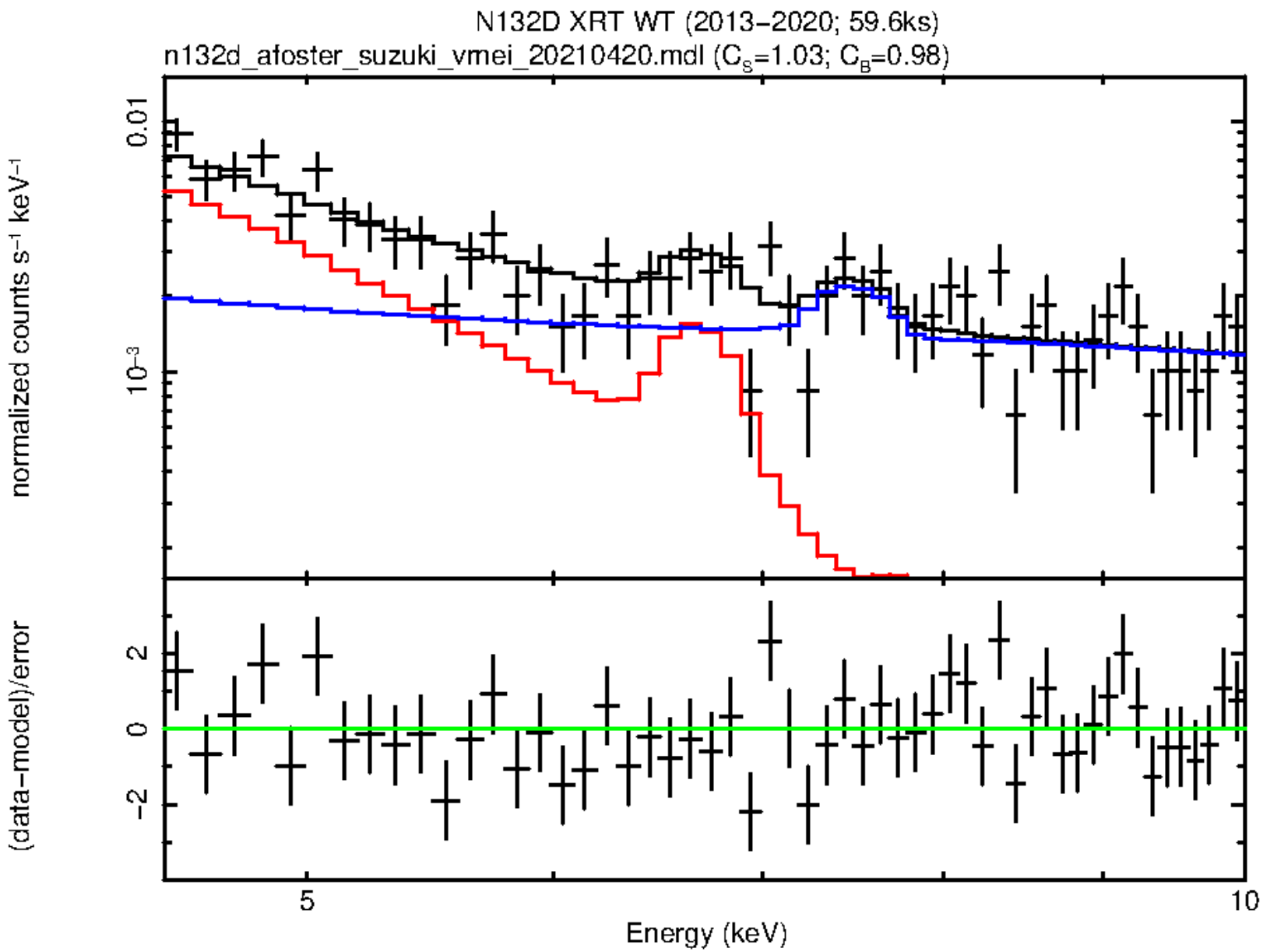
**Global Norm= 1.04,1.15**
**CStat=179**
**DOF=169**
**PChi=1.09**
**Goodness= 76.0%**



## Beardmore (Leicester)

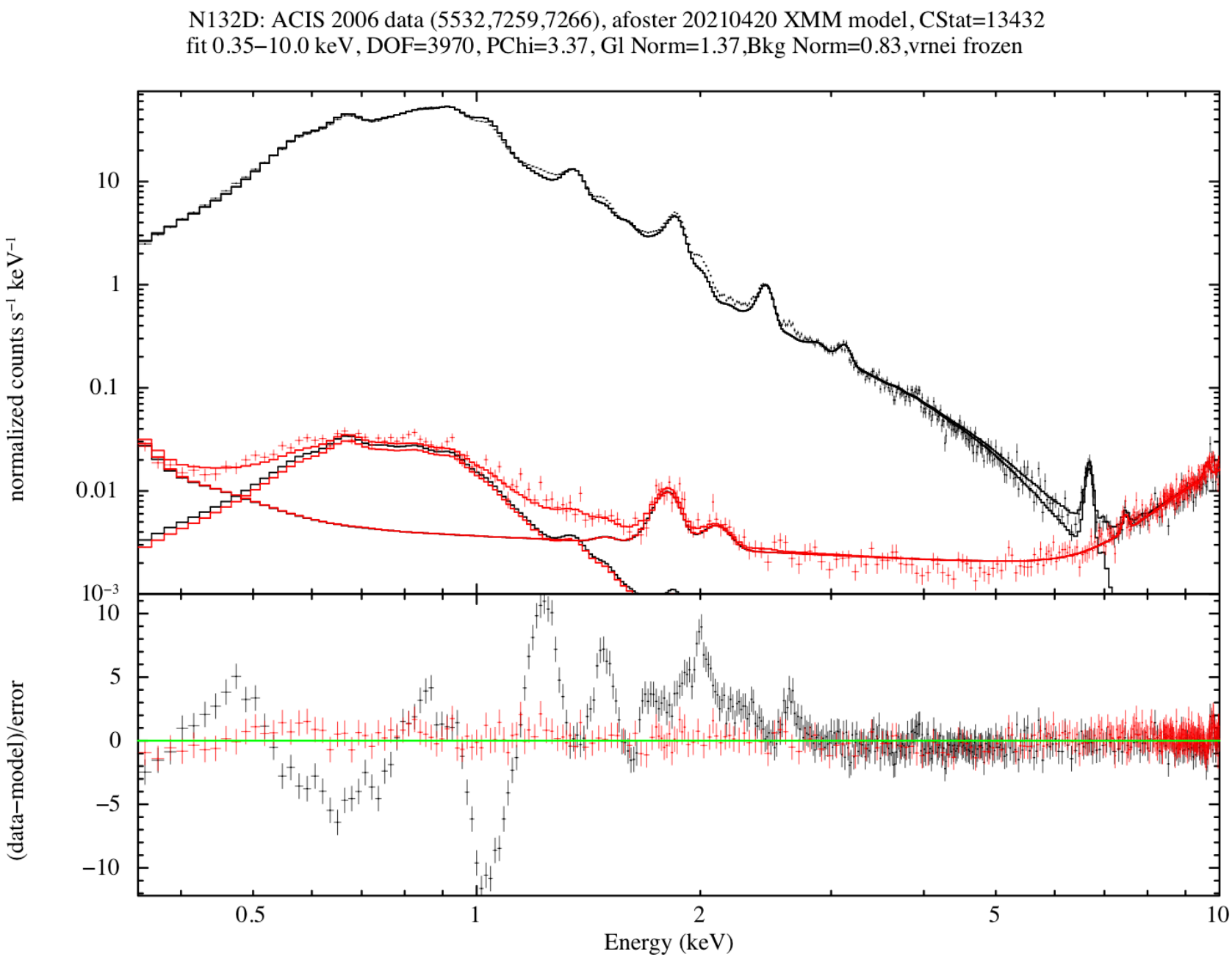
**Swift XRT: 4.5-8.0 keV physical model. Only the global norm & detector norm are allowed to vary.**

**Global Norm= 1.03**
**CStat=576**
**DOF=548**
**PChi=0.89**
**Goodness= 3.0%**



**ACIS:**
**2006 data**
**fit**
**0.35-10.0 keV**
**with the**
**physical**
**model.**
**Only the global**
**norm**
**&detector**
**norm**
**are allowed to**
**vary.**

**Global Norm=**
**1.37**
**CStat=179**
**DOF=169**
**PChi=3.37**
**Goodness=**
**100%**



## Stuhlinger (ESAC)

# N132D

Foster model:

(5.5 keV component frozen)

No fit:

Red.Chi: 54 (337104/6187)

Fit norm:

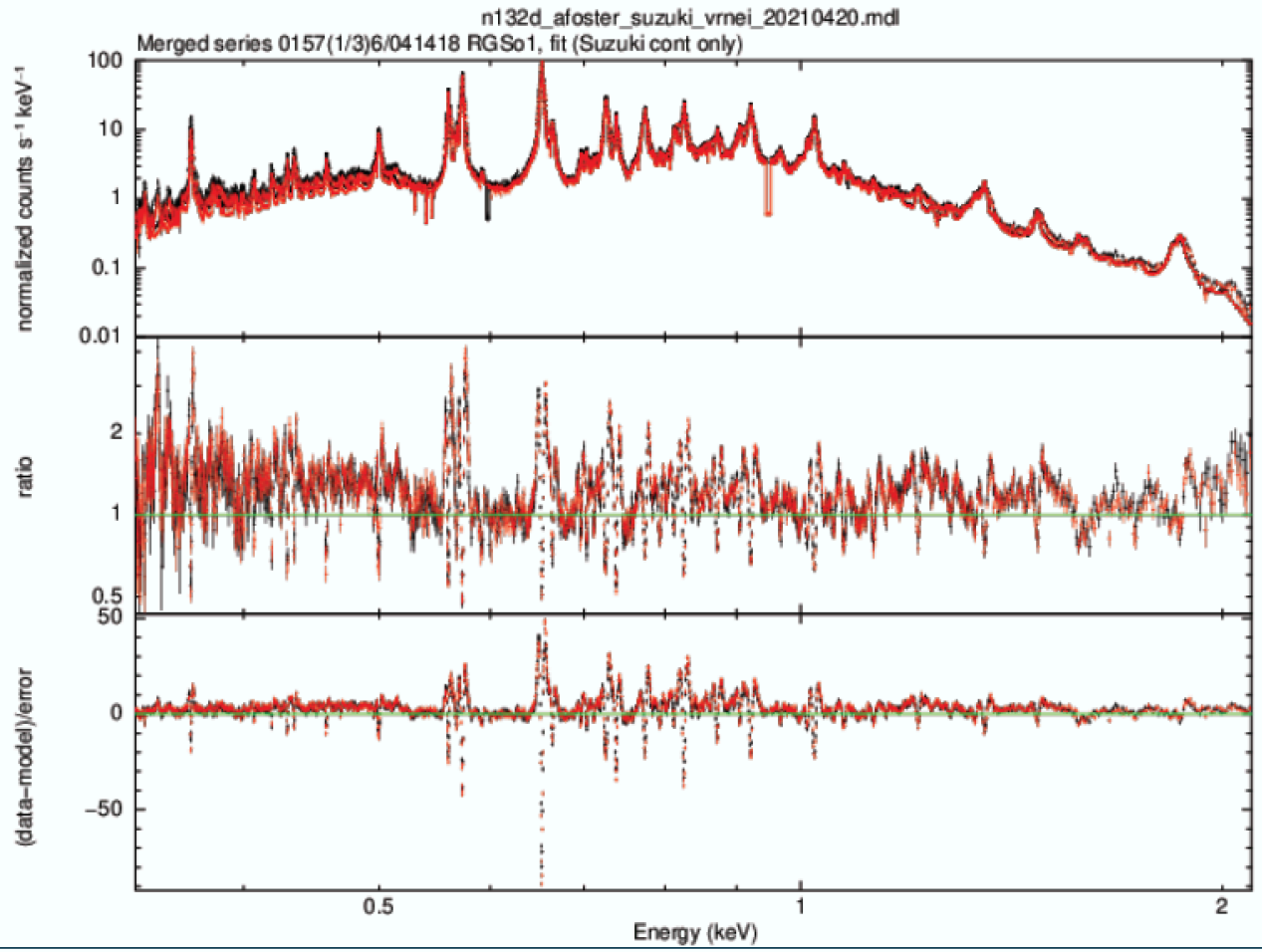
p135: 4.31616E-02+/-4.97e-05

Red.Chi: 49 (300487/6187)

Fit constant:

p1: 1.155+/-001

Red.Chi: 49 (300253/6187)

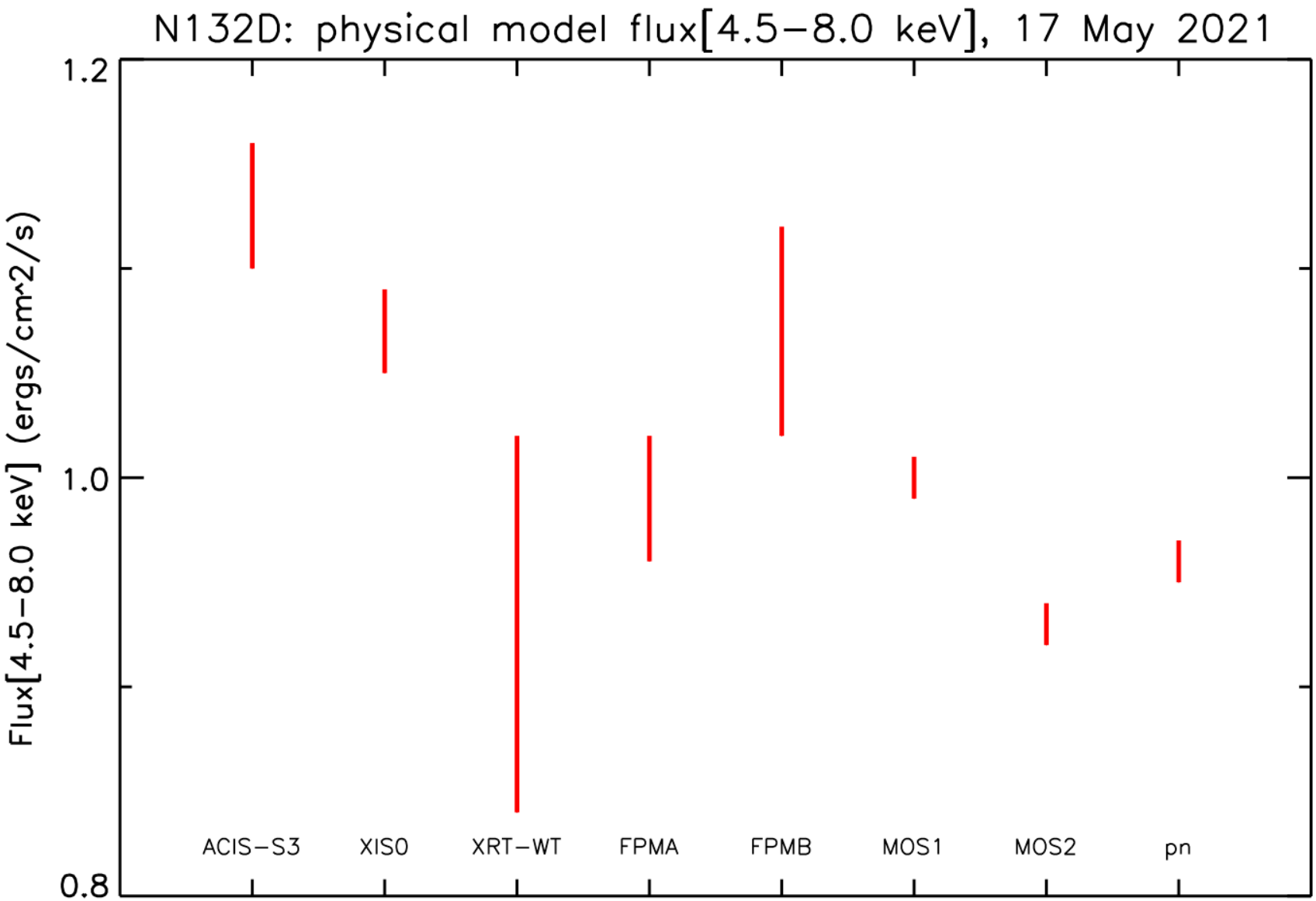



2

# Physical Model Fit Results

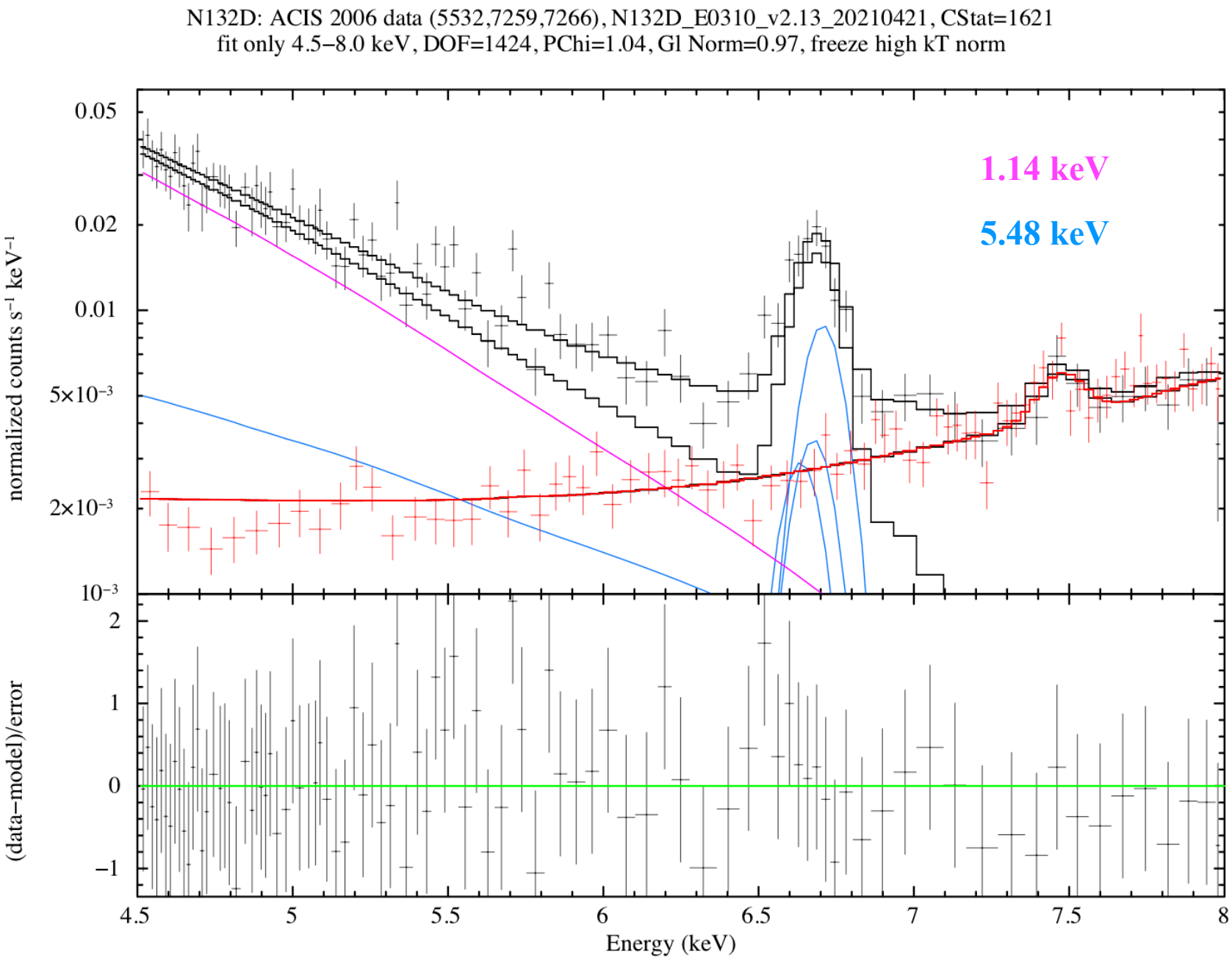
| Instrument | Gl. Norm | Flux [4.5-8.0 keV] (erg cm$^{-2}$ s$^{-1}$) | CStat | DOF | PChi | Goodness |
|---|---|---|---|---|---|---|
| initial | 1.00 | 0.94_E-12 | | | | |
| ACIS | 1.19+/-0.03 | 1.13+/-0.03 E-12 | 1617 | 1432 | 1.02 | 69% |
| Suzaku XIS0 | 1.14+/-0.02 | 1.07+/-0.02 E-12 | 522 | 481 | 1.03 | 84% |
| NuSTAR FPMA | 1.04+/-0.05 | 0.99+/-0.03 E-12 | 179 | 169 | 1.09 | 76% |
| NuSTAR FPMB | 1.15+/-0.06 | 1.07+/-0.05 E-12 | * | * | * | * |
| pn | 1.00+/-0.01 | 0.96+/-0.01 E-12 | 13122 | 11882 | 1.02 | 96% |
| MOS1 | 1.04+/-0.01 | 1.00+/-0.01 E-12 | 21288 | 26561 | 0.98 | 27% |
| MOS2 | 0.97+/-0.01 | 0.93+/-0.01 E-12 | 21681 | 26561 | 0.99 | 30% |
| Swift | 1.03+/-0.09 | 0.93+/-0.09 E-12 | 576 | 548 | 0.89 | 3% |

# Physical Model Flux Results



**ACIS: 2006 data fit 4.5-8.0 keV with the empirical model. Global norm, Fe XXV He-α norm and Fe XXVI Ly-α norm are allowed to vary.**

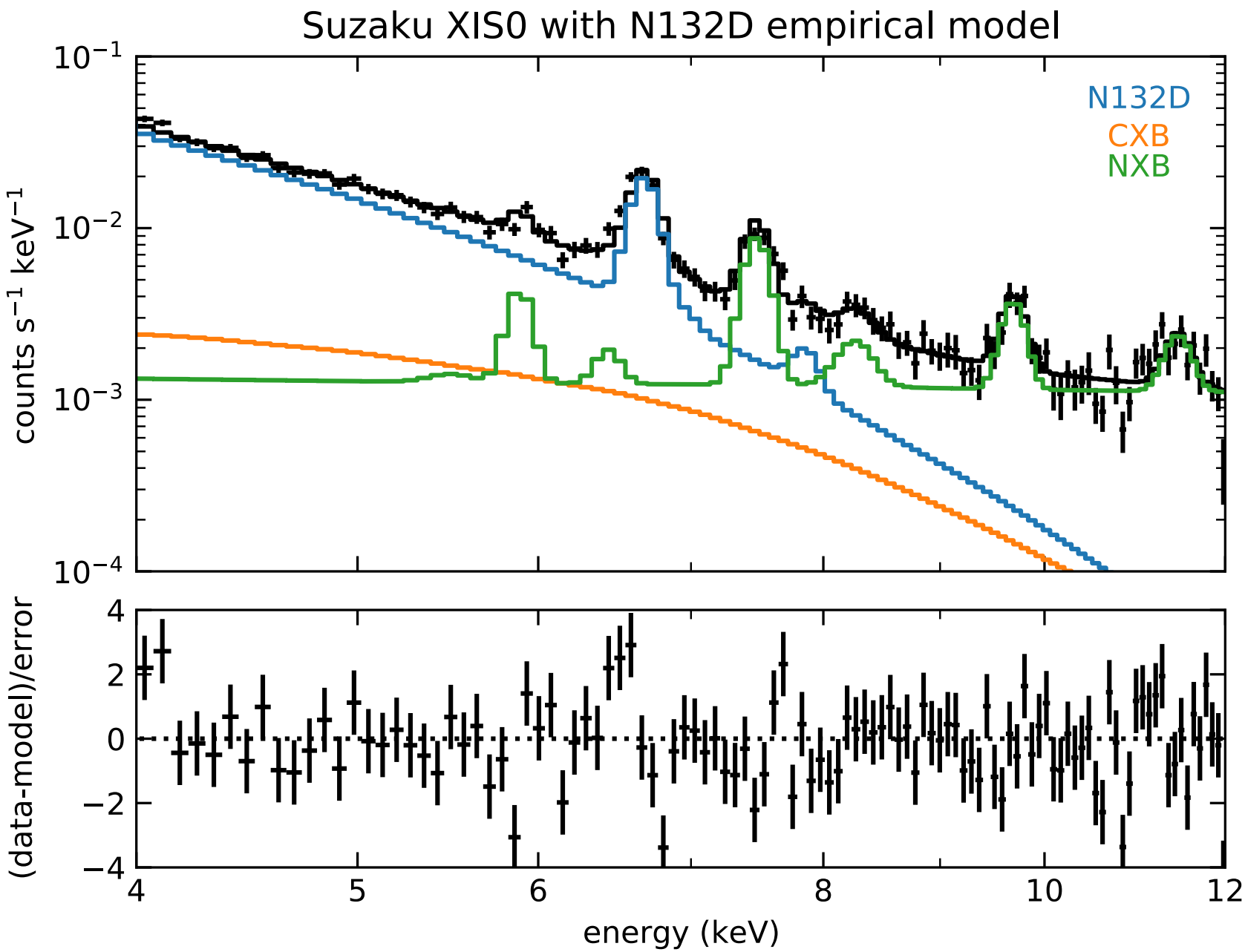
**Global Norm= 0.97**
**CStat=1621**
**DOF=1424**
**PChi=1.04**
**Goodness= 80.0%**



**Miller (MIT)**

**Suzaku XIS0: 4.5-8.0 keV with the empirical model. Global norm, Fe XXV He-α norm and Fe XXVI Ly-α norm & detector norm are allowed to vary.**

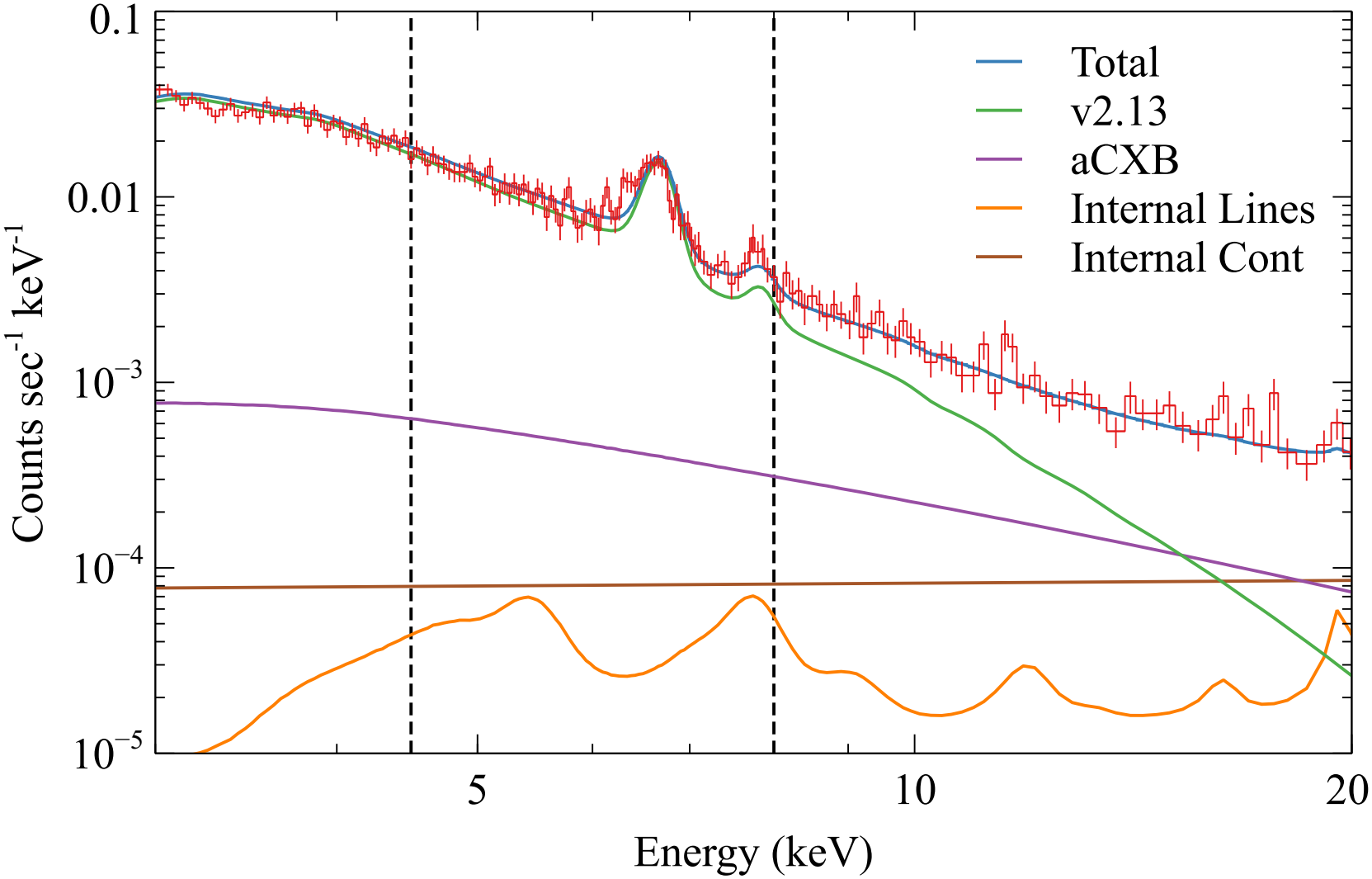
**Global Norm= 0.83**
**CStat=544**
**DOF=478**
**PChi=1.07**
**Goodness= 96.0%**



Grefenstette (Caltech)

# Empirical Model (v2.13), un-binned

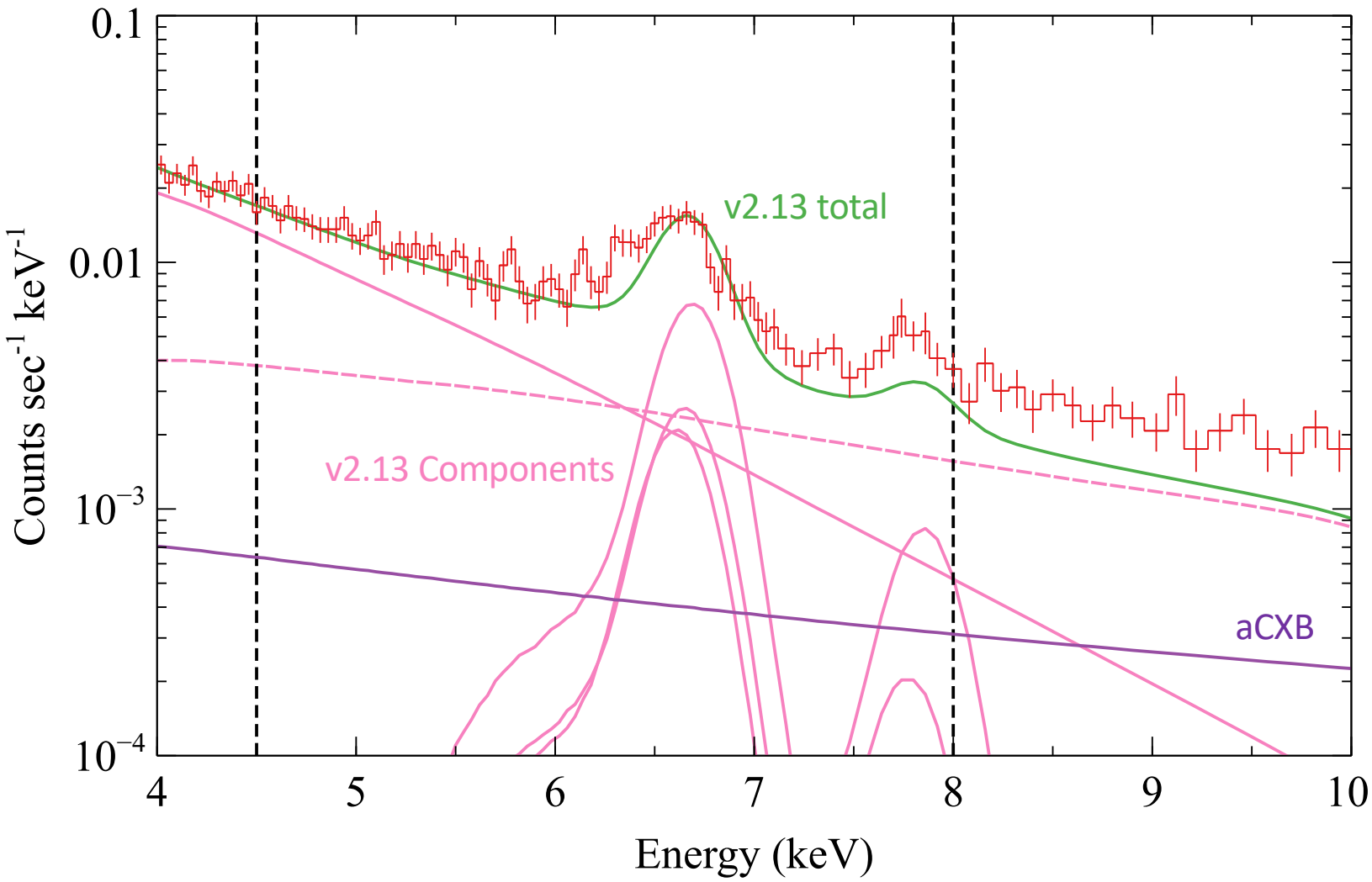
**NuSTAR : 4.5-8.0 keV FPMA&B empirical model. Global norm, Fe XXV He-α norm and Fe XXVI Ly-α norm & detector norm are allowed to vary. Global Norm= 0.79,0.87 CStat=183 DOF=168 PChi=1.10 Goodness= 87.0%**



# Empirical Model (v2.13), un-binned

Grefenstette (Caltech)

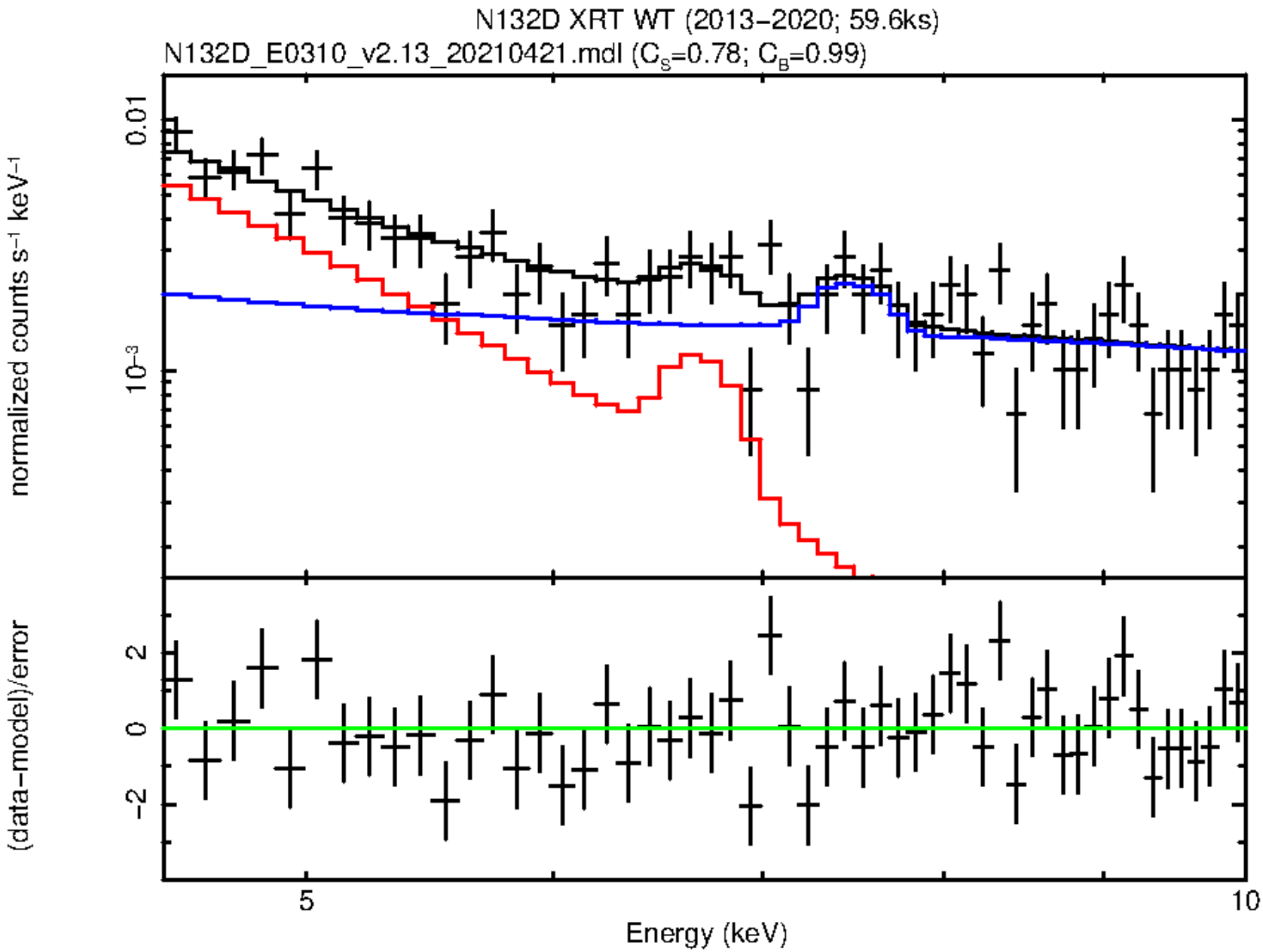
**NuSTAR : 4.5-8.0 keV FPMA&B empirical model. Global norm, Fe XXV He-α norm and Fe XXVI Ly-α norm & detector norm are allowed to vary. Global Norm= 0.79,0.87 CStat=183 DOF=168 PChi=1.10 Goodness= 87.0%**



## Beardmore (Leicester)

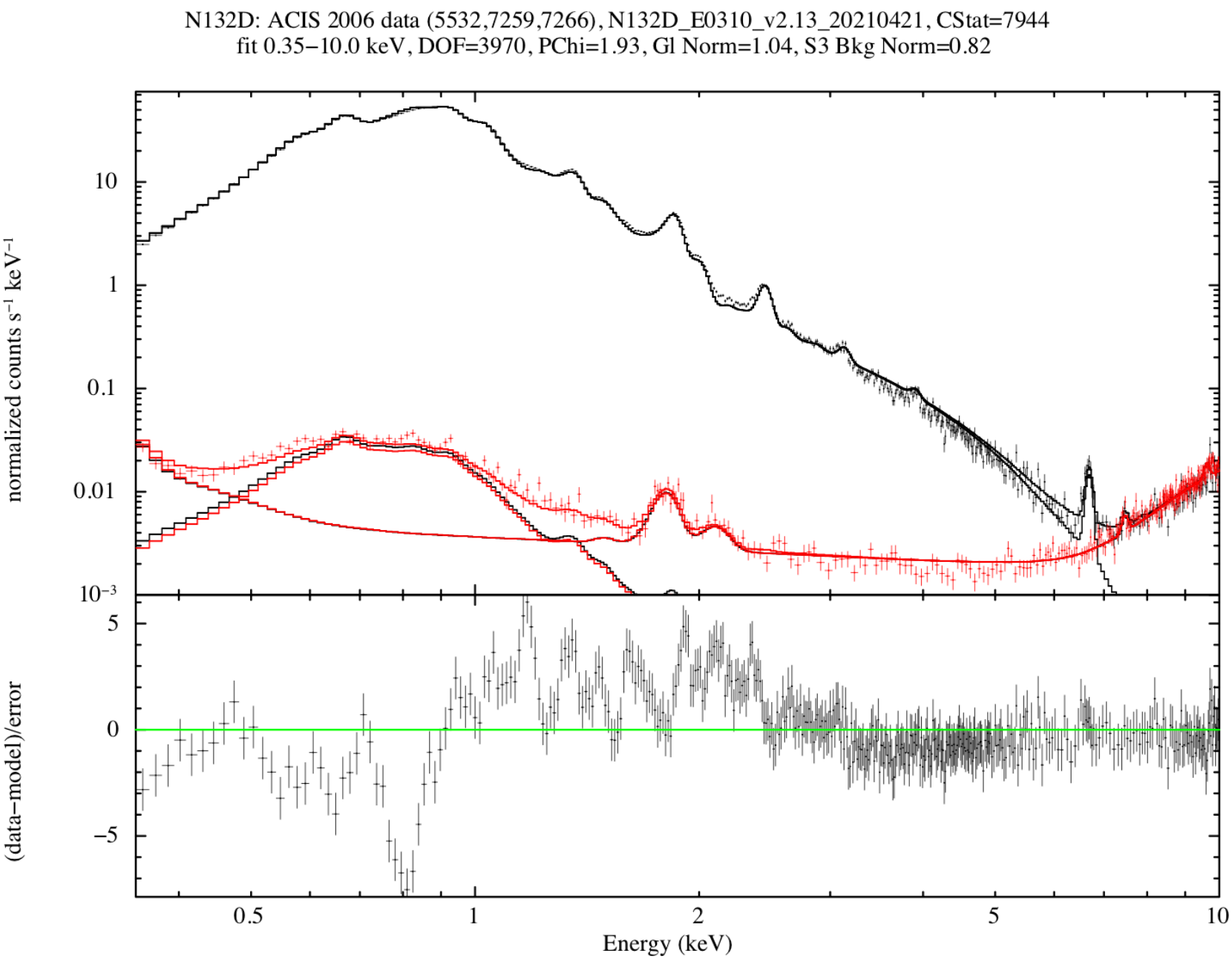
**Swift XRT: 4.5-8.0 keV empirical model. Global norm Fe XXV He-α norm, Fe XXVI Ly-α norm & detector norm are allowed to vary.**

**Global Norm= 0.78**
**CStat=574**
**DOF=546**
**PChi=0.89**
**Goodness= 3.0%**



**ACIS:**
**2006 data**
**fit**
**0.35-10.0 keV**
**with the**
**empirical**
**model.**
**Global norm &**
**detector bkg**
**norm are**
**allowed to**
**vary. All other**
**parameters**
**frozen.**

**Global Norm=**
**1.04**
**CStat=7944**
**DOF=3970**
**PChi=1.93**



## Stuhlinger (ESAC)

# N132D

RGS based model:

V2.13 continuum fixed

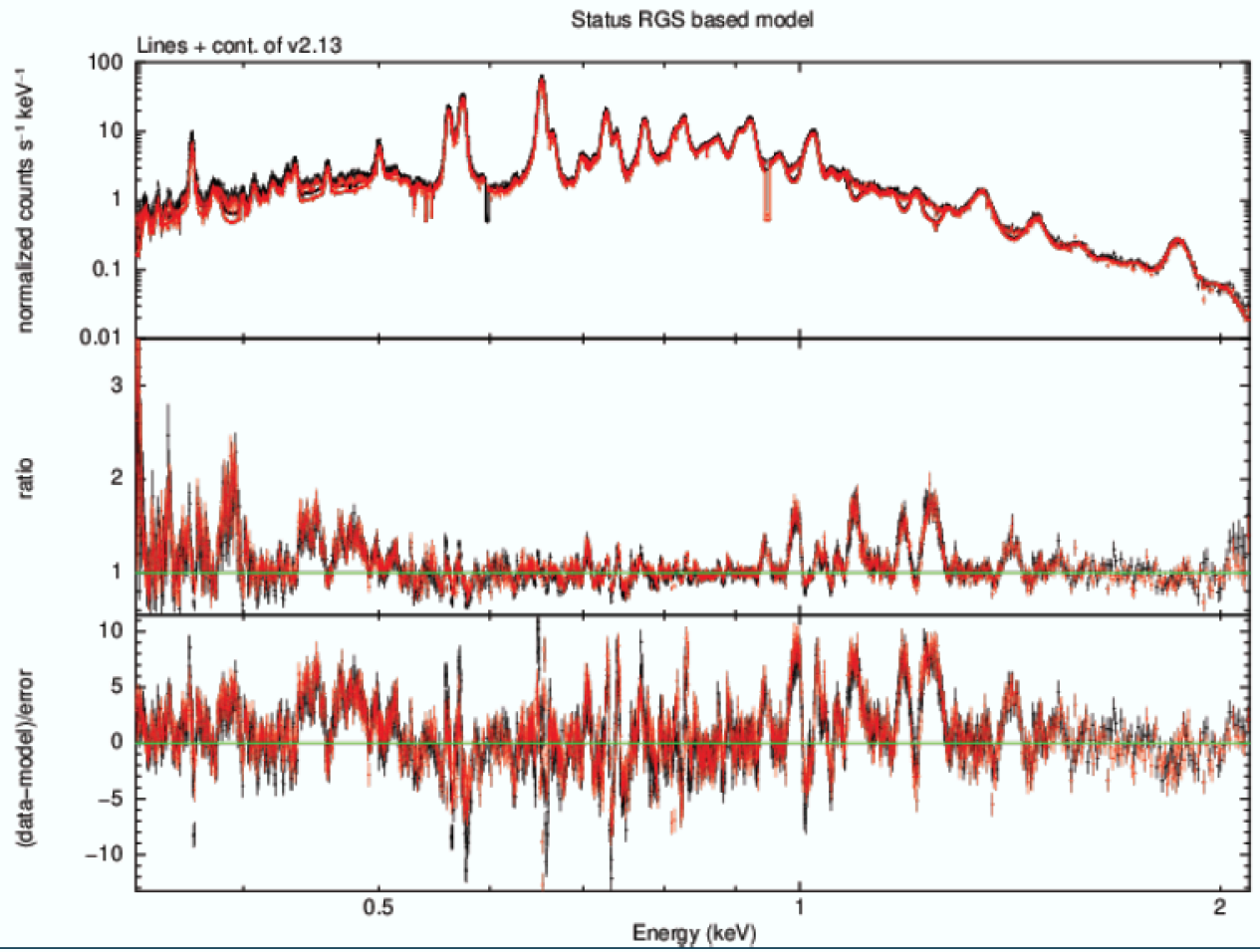
132 lines

Fit:

Red.Chi: 6 (38400/6187)

Available as:

N132D_E0310_v2.14



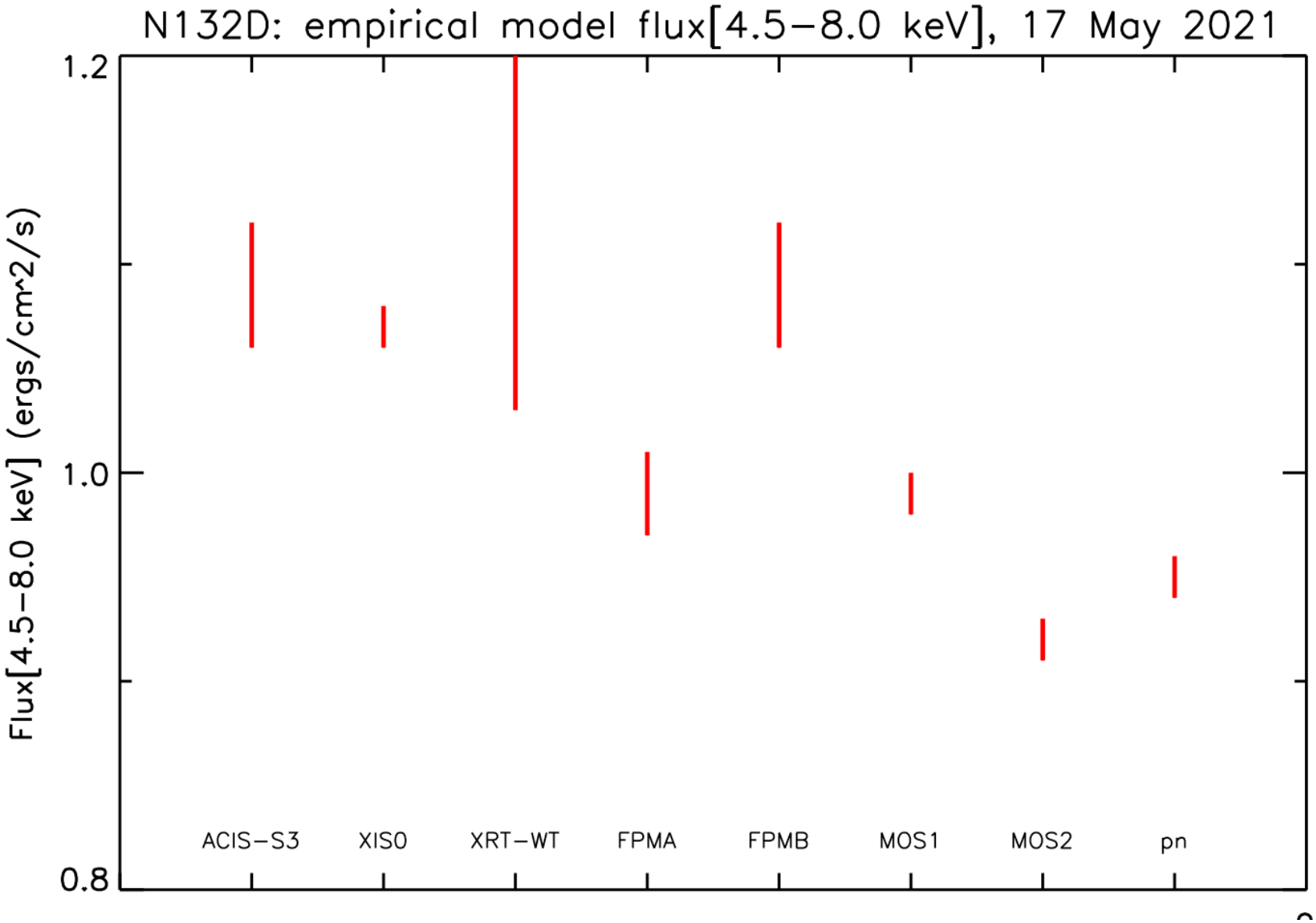

5

→ THE EUROPEAN SPACE AGENCY

# Empirical Model Fit Results

| Instrument | Gl. Norm | Flux [4.5-8.0 keV] (erg $cm^{-2}$ $s^{-1}$) | Fe XXV He-α f (photons $cm^{-2}$ $s^{-1}$) | Fe XXVI Ly-α (photons $cm^{-2}$ $s^{-1}$) | CStat | DOF | PChi | Goodness |
|---|---|---|---|---|---|---|---|---|
| initial | 1.00 | 1.24_E-12 | 3.0E-06 | 2.2E-07 | | | | |
| ACIS | 0.97+/-0.02 | 1.09+/-0.03 E-12 | 3.7+/-0.3 E-06 | 8.8+/-?? E-07 | 1621 | 1424 | 1.04 | 80% |
| Suzaku XIS0 | 0.83+/-0.01 | 1.07+/-0.01 E-12 | 3.9+/-0.2 E-06 | 13.0+/-6.0 E-07 | 544 | 478 | 1.07 | 96% |
| NuSTAR FPMA | 0.79+/-0.05 | 0.99+/-0.02 E-12 | 3.6+/-0.5 E-06 | 2.0+/-?? E-10 | 183 | 168 | 1.10 | 87% |
| NuSTAR FPMB | 0.87+/-0.04 | 1.09+/-0.03 E-12 | same | same | * | * | * | * |
| pn | 0.75+/-0.01 | 0.95+/-0.01 E-12 | 3.6+/-0.1 E-06 | 1.8+/-0.2 E-7 | 13181 | 11880 | 1.04 | 100% |
| MOS1 | 0.77+/-0.01 | 0.99+/-0.01 E-12 | 3.9+/-0.1 E-06 | 1.5+/-0.4 E-7 | 21303 | 26559 | 1.00 | 51% |
| MOS2 | 0.71+/-0.01 | 0.92+/-0.01 E-12 | 3.9+/-0.1 E-06 | 2.3+/-0.4 E-7 | 21724 | 26559 | 1.00 | 49% |
| Swift | 0.78+/-0.07 | 1.15+/-0.12 E-12 | 2.3+/-1.4 E-06 | ?? | 574 | 546 | 0.89 | 3% |

# Empirical Model Flux Results



# Conclusions

- physical model and empirical model have similar parameters for the continuum and similar strengths of Fe XXV He-α triplet, hopefully this means that the empirical model has some basis in reality
- physical model and empirical model fit equally well in the 4.5-8.0 keV band ***IF*** the global normalization is allowed to vary
- the overall shape of the spectrum is similar amongst the various instruments in this bandpass
- there are significant flux differences in this band with ACIS having the highest flux and MOS2 having the lowest flux

# Future Work

- go back to the original order of model development, low energy part first, middle energy next, high energy last
- want to preserve what we have done for the high energy part of the spectrum
- finalize the low energy part of the model, based on analysis of the RGS
- schedule: finish low energy part this summer and have candidate model for middle range BEFORE the IACHEC meeting in the Fall
- finalize the middle range model at the Fall meeting

# XMM: MOS & PN Data prep

| Instrument | N obs | Time obs (ks) | N obs used | Time used (ks) |
|---|---|---|---|---|
| PN | 54 | 670 | 17 | 355 |
| MOS1 | 50 | 884 | 38 | 830 |
| MOS2 | 50 | 1007 | 38 | 893 |

Data selected to ensure similar modes, filters and that the remnant is on the chip.

1) Detector background:

- Fit model from 4.5 to 12.0 keV. Detector BG model is loaded, but with overall norm free for each detector. Fit to get background norm, then freeze.

2) N132D fit

- Reset range to 4.5-8keV, Freeze all model components except those listed.

The Astrophysical Journal, 900:39 (13pp), 2020 September 1 https://doi.org/10.3847/1538-4357/aba524


# Plasma Diagnostics of the Supernova Remnant N132D using Deep XMM–Newton Observations with the Reflection Grating Spectrometer

Hitomi Suzuki[1,2], Hiroya Yamaguchi[2,3], Manabu Ishida[1,2], Hiroyuki Uchida[4], Paul P. Plucinsky[5], Adam R. Foster[5], and Eric D. Miller[6]

Suzuki model: 3x ionizing plasmas

- Same timescale ($\tau$=9.8x10$^{10}$cm$^{-3}$s$^{1}$)
- Same elemental abundances
- Different kT

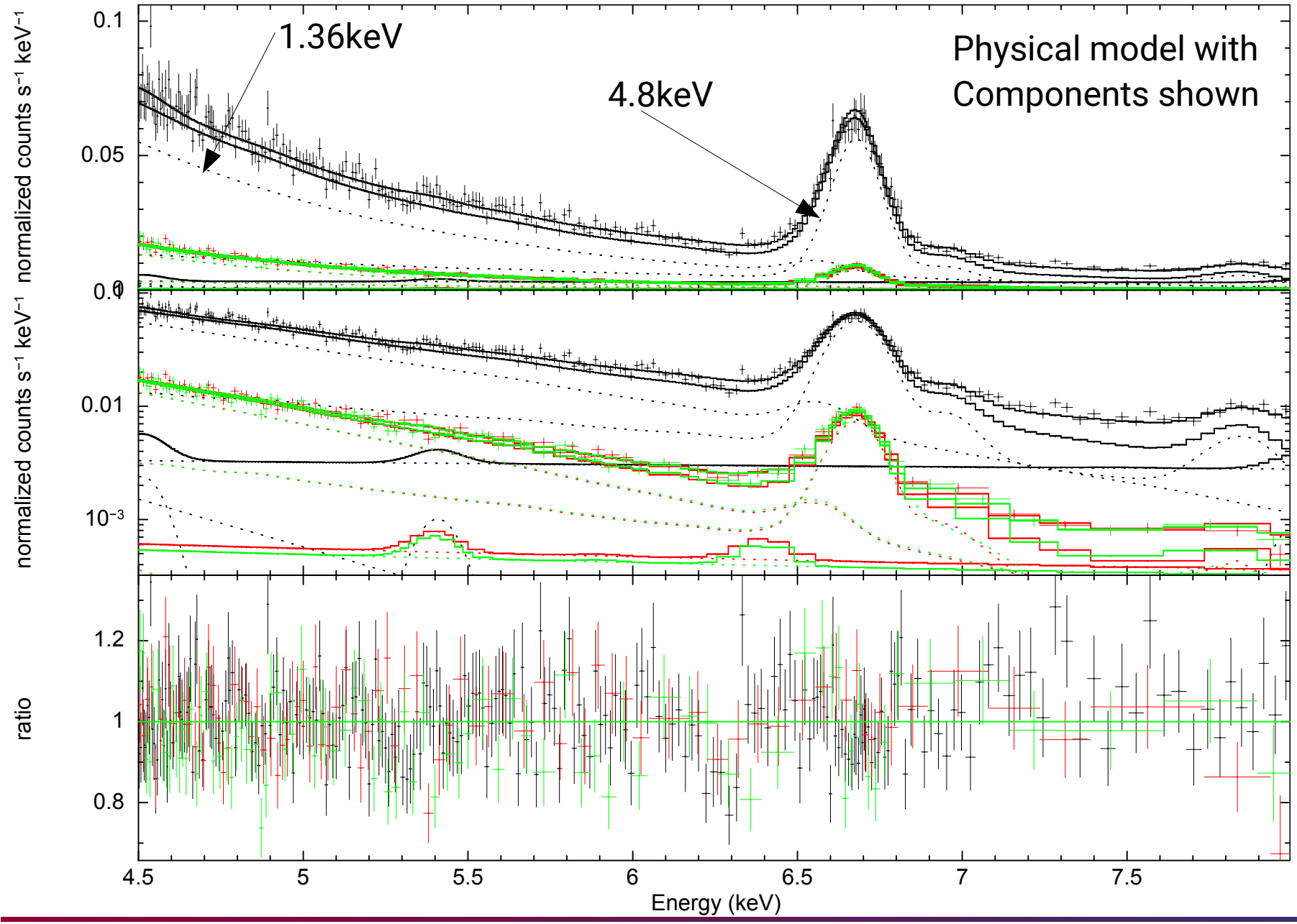
These components do not describe high kT. From Bamba+ (2018)
There is a ~5.7keV component too and evidence for a neutral Fe line.

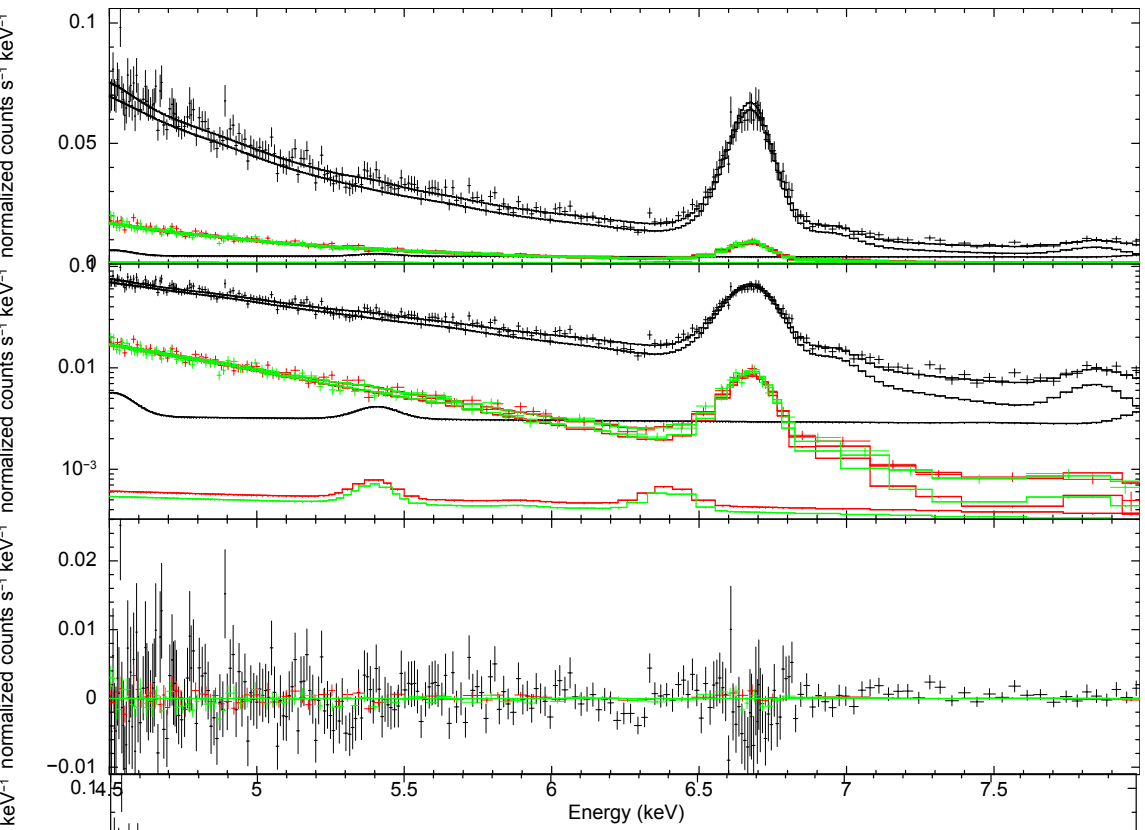
Added one extra vrnei component for high kT plasma. Set to 4.8keV based on fits to this data.

The Best-fit Parameters of the Three-temperature NEI Model

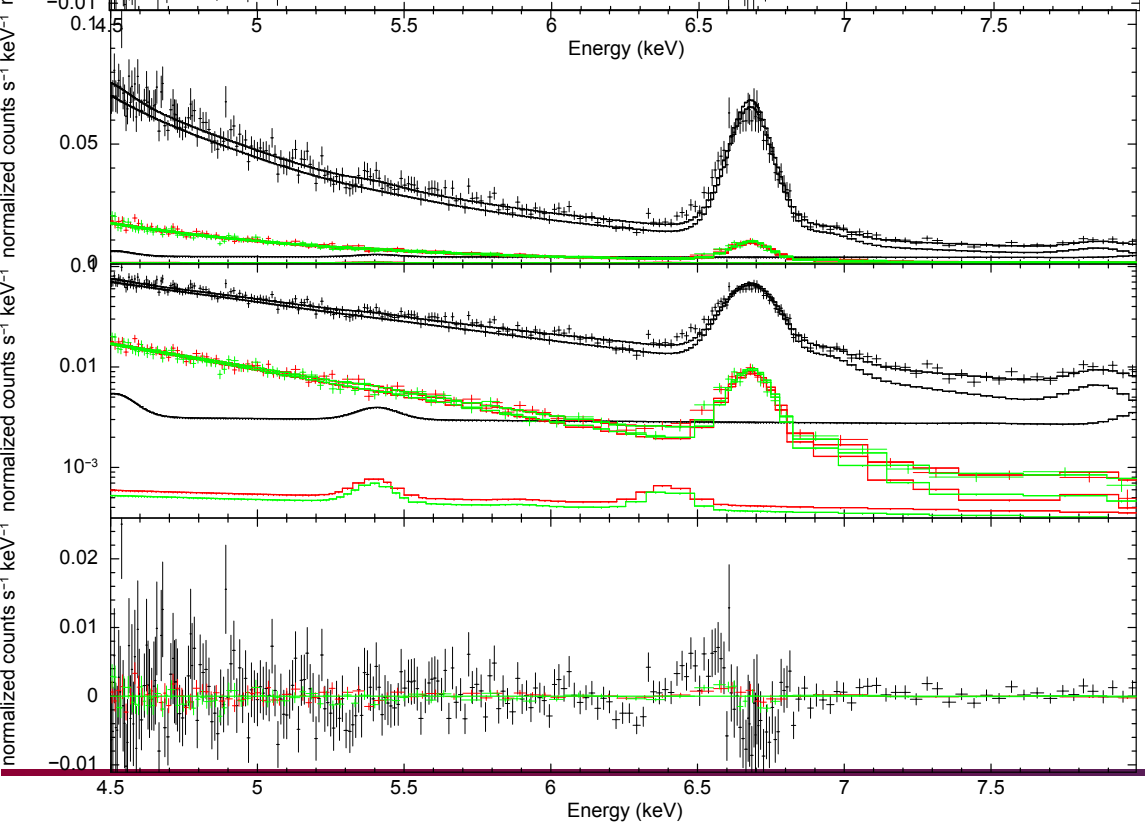
| Parameters | | |
|---|---|---|
| $N_H$ | ($10^{20}$ cm$^{-2}$) | $6.8^{+0.1}_{-0.4}$ |
| $kT_{e,\mathrm{low}}$ | (keV) | $0.200^{+0.004}_{-0.005}$ |
| $\mathrm{VEM}_{\mathrm{low}}$ | ($10^{60}$ cm$^{-3}$) | $1.31^{+0.03}_{-0.04}$ |
| $\sigma_{\mathrm{low}}$ | (km s$^{-1}$) | 438 ± 34 |
| $v_{\mathrm{low}}$ | (km s$^{-1}$) | 559 ± 18 |
| $kT_{e,\mathrm{med}}$ | (keV) | $0.563^{+0.01}_{-0.005}$ |
| $\mathrm{VEM}_{\mathrm{med}}$ | ($10^{60}$ cm$^{-3}$) | $1.52^{+0.02}_{-0.03}$ |
| $\sigma_{\mathrm{med}}$ | (km s$^{-1}$) | $445^{+21}_{-20}$ |
| $v_{\mathrm{med}}$ | (km s$^{-1}$) | 183 ± 11 |
| $kT_{e,\mathrm{high}}$ | (keV) | $1.36^{+0.04}_{-0.02}$ |
| $\mathrm{VEM}_{\mathrm{high}}$ | ($10^{60}$ cm$^{-3}$) | $0.93^{+0.05}_{-0.03}$ |
| $\sigma_{\mathrm{high}}$ | (km s$^{-1}$) | 0 (fixed) |
| $v_{\mathrm{high}}$ | (km s$^{-1}$) | −639 ± 27 |
| C | | $0.26^{+0.02}_{-0.01}$ |
| N | | $0.172^{+0.009}_{-0.010}$ |
| O | | $0.34^{+0.01}_{-0.02}$ |
| Ne | | $0.51^{+0.02}_{-0.01}$ |
| Mg | | $0.49^{+0.03}_{-0.02}$ |
| Si | | 0.59 ± 0.05 |
| S | | $0.57^{+0.06}_{-0.03}$ |
| Ar | | $0.75^{+0.09}_{-0.07}$ |
| Ca | | $0.04^{+0.12}_{-0.04}$ |
| Fe | | $0.411^{+0.014}_{-0.007}$ |
| Ni | | $0.71^{+0.11}_{-0.09}$ |
| $n_{\mathrm{et}}$ | ($10^{10}$ cm$^{-3}$ s ) | $9.8^{+0.3}_{-0.5}$ |
| $C$-statistics/dof | | 10426/7563 |

Bamba: 10.3847/1538-4357/aaa5a0
Suzuki: 10.3847/1538-4357/aba524


1.36keV
4.8keV
Physical model with
Components shown
normalized counts s⁻¹ keV⁻¹
normalized counts s⁻¹ keV⁻¹
ratio
0.1
0.05
0.01
10⁻³
1.2
1
0.8
4.5
5
5.5
6
6.5
7
7.5
Energy (keV)




Physical Model




Empirical Model

# Parameters

## Physical Model

| Instrument | GI Norm | Flux | Cstat | DOF | Pchi | Goodness |
|---|---|---|---|---|---|---|
| PN | 1.001+/-0.006 | 9.58 +/- 0.06 | 13122 | 11882 | 12160 | 96.00% |
| MOS1 | 1.039+/-0.009 | 9.95 +/- 0.09 | 21288 | 26561 | 26201 | 27.00% |
| MOS2 | 0.966 +/- 0.009 | 9.25+/-0.09 | 21681 | 26561 | 26352 | 30.00% |
| ALL | 1.001+/-0.004 | 9.58+/-0.04 | 56118 | 65006 | 64762 | 27.00% |

## Empirical Model

| Instrument | GI Norm | Flux | Fe XXV He-a (E-6) | Fe XXVI Lya (E-6) | Cstat | DOF | Pchi | Goodness |
|---|---|---|---|---|---|---|---|---|
| PN | 0.749+/-0.005 | 9.52+/-0.06 | 3.55+/-0.07 | 1.80+/-0.21 | 13181 | 11880 | 12336 | 100.00% |
| MOS1 | 0.767+/-0.008 | 9.87+/-0.10 | 3.86+/-0.14 | 1.46+/-0.38 | 21303 | 26559 | 26513 | 51.00% |
| MOS2 | 0.711+/-0.007 | 9.22+/-0.09 | 3.89+/-0.14 | 2.26+/-0.39 | 21724 | 26559 | 26588 | 49.00% |
| ALL | 0.743+/-0.004 | 9.51+/-0.04 | 3.68+/-0.06 | 1.83+/-0.17 | 56242 | 65004 | 65486 | 82.00% |